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LOAD BALANCER WITH AUTOMATIC LIFTING FORCE COMPENSATION

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Abstract *The most simple and usual way to handle material is to use so called conventional devices like hydraulic jacks, cranes and pulley systems. There are also specific devices, which use counterweights or springs to balance the weight and assist the material handling. For more specific applications a robot manipulator is used. Comparing these two solutions, it is possible to say that the conventional devices have the advantages such as low cost and simple operation. On the other hand, robots provide fast and accurate operation, but they have limitations in the working range. Conventional solutions offer more flexibility. In this context, this work describes the study and the development of a new mechatronic device that can be classified as an intermediate solution, between the conventional device and the robotic solution. The newly proposed solution is based on a mechanism in which: a lever system lifts the load and, instead a counterweight, a gas spring provides the lifting force. This results in a simple mechanism, lightweight, compact in size, easy to operate and low cost. However due to the simplicity, the load is perfectly balanced only in some restricted positions in the working volume, not allowing perfect balancing in all working volume. To solve this problem, a control system is coupled to the lever and gas spring mechanism. The control system is composed by a sensor, that constantly monitors the inclination of the lever, a PLC (Programmable Logic Controller) to execute a control algorithm and an electric motor to correct the gas spring position. Thus, the lifting force is constantly corrected, achieving a perfect balancing at any position. Besides, the control system allows automatic adaptation of the device to work with different weights. The study is developed assuming a specific application: reduce the effort of an electrician to handle a hydraulic saw of around 8 kg weights, during the tree trimming procedure. The prototype is developed, constructed and tested. Tests show the effectiveness of the proposed device.*

Keywords: *material handling, load balancer, mechatronics, robotics, force control, tree trimming*

1. INTRODUCTION

In a general manner, solutions employed to handle materials can be divided into two groups: the conventional devices that included jacks, cranes or rope hoists, and the robotic systems. There is a third group, a sort of specific devices and the intelligent assist device (IAD) (Kruger *et al.* (2006)) that still consists object of studies. One of specific devices is illustrated in Fig.1. This device uses a counterweight to create the required force to manipulate the load. The force generated by the counterweight is transmitted to load by a link mechanism. The most limitation of this kind of mechanism is that the design of the mechanism is not simple (Hirose *et al.* (2003)).

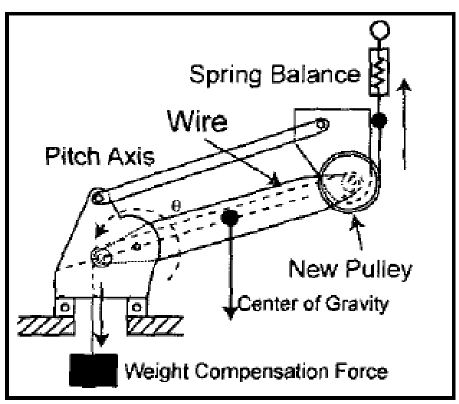

Figure 1 Schematic of a float-arm, a sample of specific device (Hirose *et al.* 2003)

The intelligent assist devices (IAD) are devices developed to combine the advantages of robots, i.e. accuracy and speed, with the versatility and of conventional devices. Thus, IAD can be classified with an intermediary solution, as illustrated in Fig.2 (Kruger *et al.* (2006)). Differently of robots that execute the task under high level of autonomy, IADs work together with the operator. Although the IAD do not achieve de same accuracy and speed of a robot, the manipulation task is commanded basically by the human operator (Surdilovic *et al.* (2003)). The IAD can be classified

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in three larges groups: Cobot – Collaborative Robots (Peshkin and Colgate (1999)), Cooperative Robots (Kosuge and Kazamura (1997)) and Power extenders (Kazerooni (1990)).

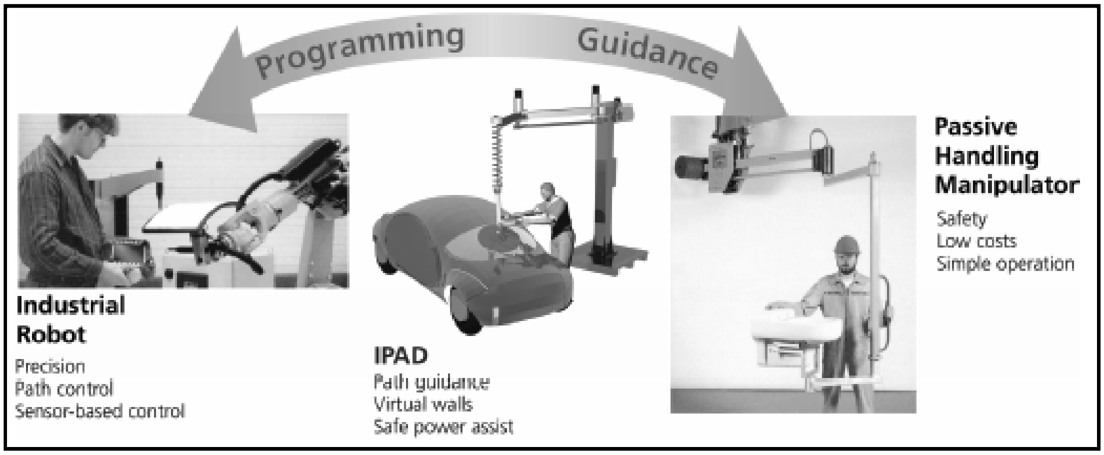

Figure 2 The Intelligent Assist Device concept (Kruger *et al.* (2006))

1.1. Cobot

The Cobot (Collaborative robot) is a new architecture of robot featuring as the main characteristics the passivity and the fact that it works with virtual surface. The passivity allows the Cobot to work together with the human operator. The operator pushes or pulls the Cobot to moving it. The actuators present in the Cobot only avoid the operator to reach a forbidden area, or transpose a surface determined virtually, i.e., a virtual surface, as describes in Worsnopp *et al.* (2006) and Peshkin *et al.* (2001). Due to this architecture and working principle, the Cobot are an interesting solution in terms of robustness and ergonomics. The main criticism to the Cobot is the low or null reduction in the effort made by the operator, since the operator has to provide all power to move the load by the Cobot. This device is a category of IAD that focuses only on the control the position of the load (Kochan (2004)); does not consider reduction in the effort to manipulate a load.

1.2. Cooperative Robots

The cooperative robot is another architecture of robots which has many proprieties to allow this device to work together with the operator. It differs from the Cobot, since it moves by itself, almost eliminating the manipulation effort. However, the device motion is completely determined by the operator, who controls the robot using a remote control or force sensors (Lee *et al.* (2007)). Cooperative robots are very similar to industrial robots and this is the negative aspect of this kind of device. This IAD needs large actuators, occupies a large space and represents a complex solution (Ohya, 2002).

1.3. Power extenders

The power extender is a device similar to a suit. The operator wears an exoskeleton type device that moves exactly as the operator moves, but achieving large forces. Compared to other IADs, this device allows the execution of a wider range of tasks; it does not need a large space and provide large guidance to the operator (Yamamoto *et al.* (2003) and Kigushi *et al*. (2003)). Despite these advantages, the power extender needs a great number and type of sensors to monitor the motion of the operator and thus, avoid accidents; also, the exoskeleton uses specially compact actuators and batteries to avoid limiting movements of the operator. These aspects make power extenders heavy, complex and expensive (Damme *et al.* (2005)).

In this scenario, this paper describes a device that has characteristics between robotic solution and convectional solution; like an IAD. However, the device, here presented, prioritizes the guidance, has as the main function the reduction in the effort to manipulate materials, is simple and is low cost.

2. PROPOSED DEVICE

The proposed study aims the development of a device, that prioritizes the guidance and the simplicity and, for this reason it chooses a simple mechanism, which duty is to move the weigh in the range of the radius, both vertical and horizontal, reducing the effort to keeping the position or moving the load to determined position. This device can be coupled to a trail or a road system to allow manipulating weights with more degree of freedom improving the range reachable and increasing the applications possibility.

This study is based on a mechanism design to manipulate materials using springs. It is simplified to facilitate the manufacturing and rise up the robustness. However, due to the simplicity, the load is perfectly balanced only in some restricted positions in the working volume, not allowing perfect balancing in all working volume.

To solve this problem, a control system was developed and implemented on mechanism. The electric motor used requires a low power and low electric energy, because the mechanism balances the weight on part of working volume.

The position of the weight is responsibility of human operator and the control system is responsible only to balance the weight on all working balance, making the control algorithm much more simplified.

The study is developed assuming a specific application: reduce the effort of an electrician to handle a hydraulic saw of around 8 kg weights, during the tree trimming procedure on electric distribution. Besides, other applications are not discarded.

2.1. Mechanical Part

The study of the load manipulation problem starts with the one of the simplest mechanical solution, i.e., a lever mechanism shown in Fig.3. In one extremity of the level, the load to be manipulated is hanged and, in the other extremity, a counter-weight. A perfect balancing of the weight is obtained if the counter-weight mass m is as follows.

$$m = \frac{1}{g}\frac{L_1}{L_2}.P \qquad (1)$$

Here g is the gravity constant, L_1, the length of the lever arm at the load side, L_2, the length at the counter-weight side and P the load force.

The lever mechanism of the Fig.3 enables the motion of the load only vertically. To manipulate the load, it is necessary to have possibility of moving the load in other directions, transporting it to different positions. This is simply achieved, for example, by suspending the described lever mechanism in a base equipped with wheels. Besides this solution, many other solutions are possible. This does not represent some difficulties in the problem of load manipulation. The most interesting problem to be analyzed is the lever mechanism. For this reason, only the lever mechanism will be treated forward.

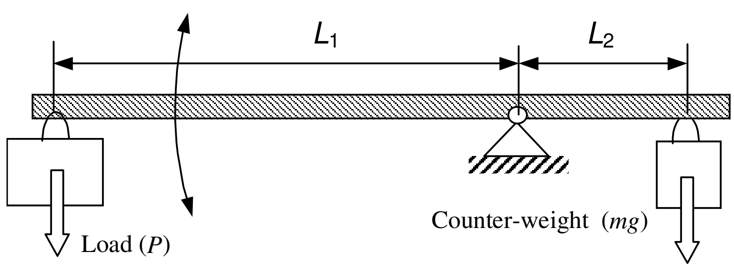

Figure 3 The Schematic of a lever mechanism

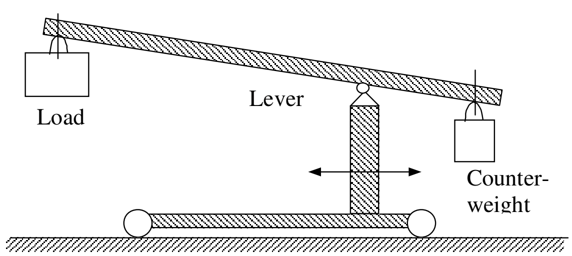

Figure 4 Mobility in the horizontal plane

Although very simple in concept and simple to implement, the lever mechanism based on the use of the counter-weight make the device heavy: the load supported by the moving base mentioned in Fig.2, must support the load and the counter-weight. Moreover, if a long arm is selected to the counter-weight side (L_2), the device becomes larger. Here, a first improvement can be introduced. The use of springs instead counter-weight. However, the usual spring introduces

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a problem. The force generated the spring varies as the spring is deformed, given rise to difficulties on balancing the load at different inclinations of the lever. Instead conventional springs, the gas spring is elected. The gas spring is a piston and a cylinder containing pressurized gas. As the piston is compressed, the gas inside the gas spring is compressed and the piston moves with respect to the cylinder. Since variation in volume of the gas is small, the gas spring reacts against an external force with nearly constant force. It is a solution equivalent to use a coil spring with a natural length very large compared to the deformation imposed to it. A sort of gas springs, with different forces is available in the market. Replacing the counter-weight with the gas spring in the mechanism of Fig.3, the schema of Fig.5 is obtained. The gas spring provides a lighter and more compact device. However, the solution presented in Fig.5 brings some new problems. The first problem is that the nominal force of the gas spring is not exactly equal to that force necessary to balance de load. This is simply solved by imposing an angle δ relative to the vertical. The other, and more difficult problem arises from the fact that the extremity of the gas spring is fixed to the device base for simplicity. Thus, as the level is inclined by α, the angle σ, according to which the gas spring force acts to the level, varies.

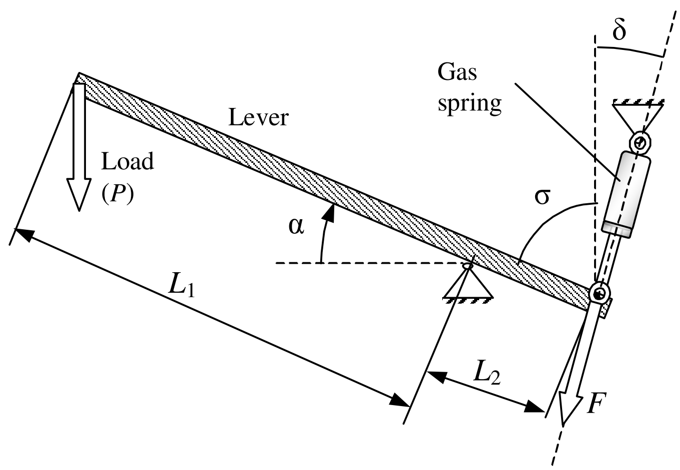

Figure 5 Schema of the lever mechanism that use the gas spring

Under these conditions, the balance force (F) suffers a variation depending on the inclination of the lever, as given by following equation.

$$F = \frac{P.L_1}{L_2.sen(\sigma)} \tag{2}$$

The angle σ is a function of α, as given by following equation.

$$\sigma = \alpha + arctg\left[\frac{L_2.(1-\cos\alpha)}{c - L_2.sen\alpha}\right] + \frac{\pi}{2} \tag{3}$$

In above equation, c is the distance between spring fixation and the lever arm when α is 0.

With the device depicted in Fig.5, large part of the load is balanced and the operator exerts considerably lo efforts to manipulate the load, compared with the direct manipulation. However, the load balancing is not perfect as Eq.(2) shows. For illustration, some parameters are assumed as shown in Table 1, replaced in Eq.(2) and simulated. Results are shown in Fig.6, where the ordinate axis is the effort exerted by the operator; this is the force necessary to keep the position of the lever with weight. The graph shows that depending on the value of α, the balance force f becomes smaller or larger than the load P, requiring an effort of the operator to keep a determined position. The load balancing is not perfect in all working volume.

There would be the possibility of correcting this imperfection of the balance force by adding mechanical solutions to move the gas spring fixation point as the arm inclines. Providences in this sense were adopted in a complex mechanism called as float arm, proposed by Hirose (2003). However, aiming simplicity in the mechanical design, this work proposes a mechatronic solution. Therefore, a correction system is attached to the mechanism presented in Fig.5. This system composed by: a sensor that monitors the lever inclination, an electric motor driven mechanism that moves the fixation point of the gas spring and a controller that regulates all system.

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Table 1. Parameter for simulation

Variable	Valor
P (load weight)	55.15 N
f (gas spring force)	300 N
L_1 (weight arm)	0.680m
L_2 (gas spring arm)	0.125m
α (working position)	–0.4363 to 0.4363 rad
c (α=0, gas spring length)	0.250mm

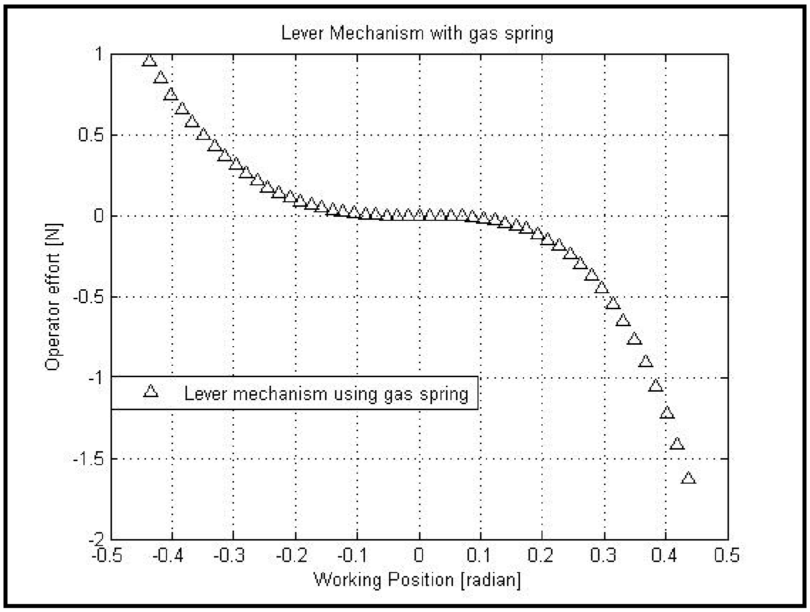

Figure 6 Operator effort versus working position in lever mechanism using a gas spring.

2.2. The correction mechanism

In order to keep the perfect load balancing in all working volume, it is necessary to keep constant the angle between the balance force and the arm of the lever in all working volume and the value of this angle depends of the value of the load applied on mechanism. Following these conditions the gas spring behaves like a counterweight. For that goal, a mechanism is designed to move the fixation point of the gas spring as shown in Fig.7.

In the correction mechanism, a motor driven screw moves a nut along vertical direction. As the nut moves, a guiding pin, connected to it, moves along a slit of the adjusting plate. This makes the plate rotate to the left or the right of the figure. Thus, the position of the extremity of the gas spring is moved to the left or the right.

The following equation gives the counter balancing force F_c at the point the load is applied as a function of the working position (α) and the inclination of the adjusting plate (β). Remaining parameters are distances shown in Fig.7.

$$F_c = \frac{F.L_2.sen\left(\alpha + 2.arctg\left[\frac{L_2.(1-\cos\alpha)}{c - L_2.sen\alpha}\right] + \frac{\pi}{2} + acrtg\left[\frac{R_2.sen\beta - L_2(1-\cos\alpha)}{L_2.sen\alpha - R_2(1-\cos\beta)}\right]\right)}{L_1} \quad (4)$$

The next equation shows the β as function of vertical position of the nut (y)

$$\beta = arcsen\left[\frac{\sqrt{y_0^2 + R_1^2}.sen\left(\gamma - arctg\left(-R_1/y_0 + \pi\right)\right)}{\sqrt{y^2 + R_1^2}} - \gamma - arctg\left(-R_1/y + \pi\right)\right] \quad (5)$$

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In Eq.(5) y_0 is the position of the nut when $\beta = 0$, γ is the angle denotes the inclination of the slit with respect to the line passing through the adjusting plate pivoting point and the gas spring fixing point.

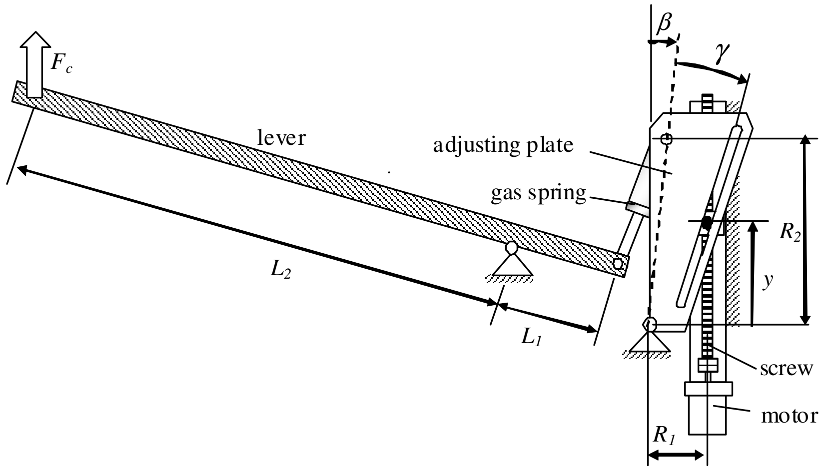

Figure 7 Lever mechanism with the gas spring and the correction mechanism.

2.3. Control System

Using the previously described correction mechanism, imperfections in the load balancing can be corrected. To facilitate the operation of the device, it is desirable that the correction is done automatically. An alternative to this is to compose a closed loop control system. However this strategy, that means the execution of the force feed-back, implies in the use of force or acceleration sensors (see for example, Lee *et al.* (2007)). Besides increasing the cost of the device, these sensors increase the complexity of the control system. In this work, it is considered that the load during the manipulation is moved with relatively low speed, so that the dynamics of the mechanical parts of the balancing device can be ignored. Thus, an open-loop control strategy is employed. The basic idea is to first, obtain a calibration table of the device, i.e., experimentally measure, for a given load (P), the position (y) of the nut (Fig.7) for each angular position of the lever, α necessary to completely balance that load. Then, when operating the balancer, the nut position is adjusted based on the measurement of the lever inclination and the calibration table.

Besides correcting imperfections in the balancing force, the correction mechanism can also be used to adapt the device to handle different loads. Rigorously, if the load changes, a new calibration table has to be obtained. But one simple alternative is to use the same calibration table but shifting all values according to the nut initial position. To obtain this initial position, the operator keeps the lever in the horizontal position (α=0) and switches manually the motor, moving the nut, until the new load is completely balanced. This would be an approximate solution. Another alternative is to, instead obtaining experimentally the calibration table, generate it by using Eqs.(4) and (5).

The Figure 8 shows the architecture of the control system showing their main elements. It includes the lever mechanism counter balanced with a gas spring, the motor driven compensation mechanism, an angular position sensor for the level (working position sensor), a sensor for nut position, a controller and a human machine interface (HMI). The controller receives the signal from the working position sensor. Then, based on the calibration table, the control algorithm determines the new position of the nut and finally, the controller activates de motor until the nut reaches the determined position. In practical terms, the position of the nut can be measured and controlled by counting the number of turn in the screw thread. The HMI is necessary only for presetting the device, when for example, the load to be manipulated changes. Fig.9 shows the flowchart of the control algorithm that can be implemented for example in a PLC (Programmable Logic Controller).

3. EXPERIMENTS

3.1. Simulation

Figure 10 shows simulations of the operator effort using the proposed device, for different working positions (α). Using Eqs.(4) and (5), for each value of α, the position of the nut (y) is calculated so as to make null the operator effort, i.e., the difference between the load (P) and the balancing force (F_c). For comparison, the effort in the case of the mechanism having only the gas spring is presented in the same figure. Because Eqs.(4) and (5) are solved by iterative method, some numerical error remained in the results. Despite these errors, the compensation error correction is achieved along all working positions.

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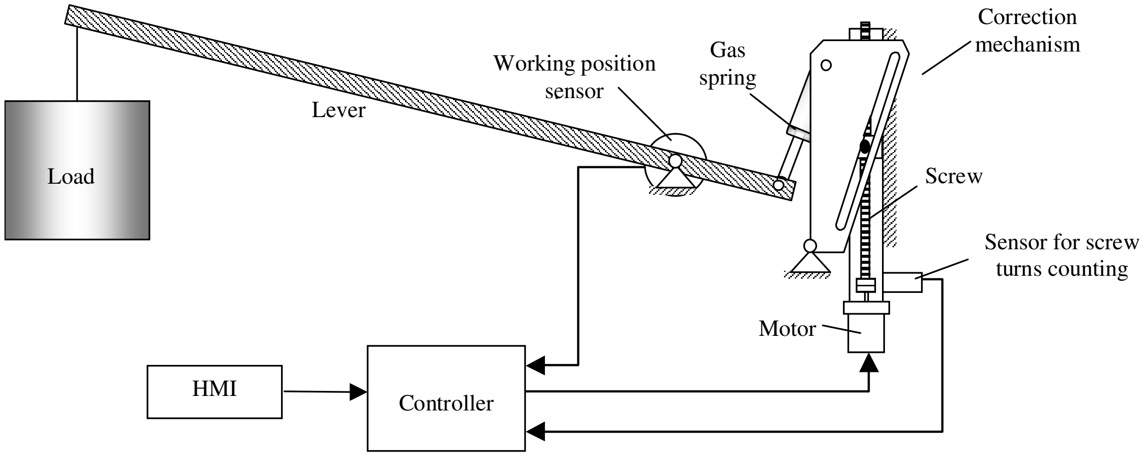

Figure 8 Schematic diagram of the control system.

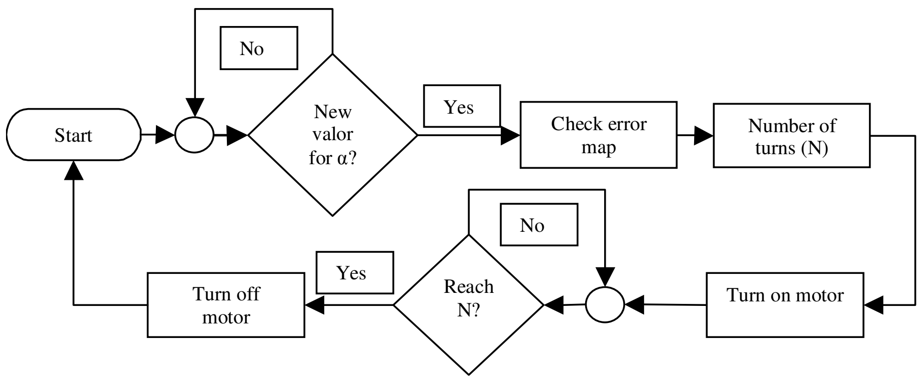

Figure 9 Flowchart of the control algorithm

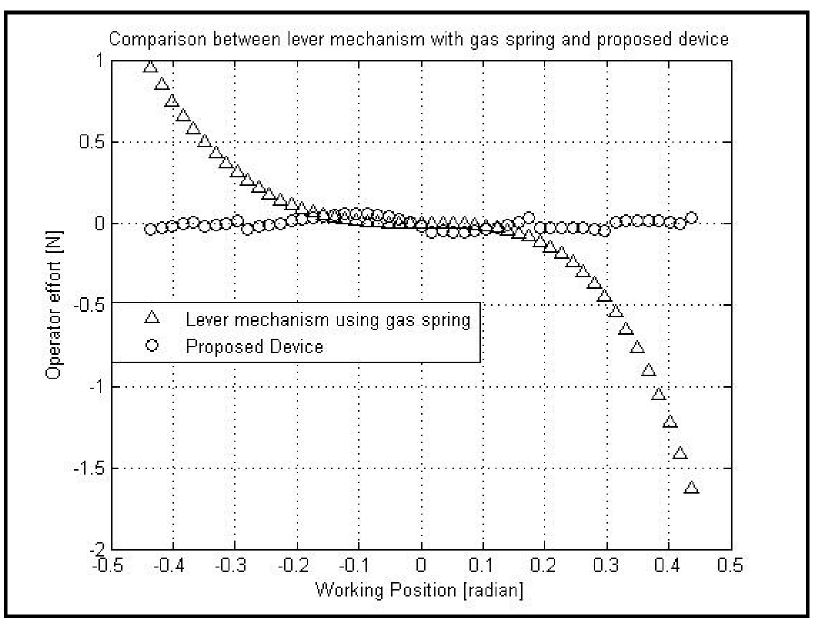

Figure 10 Diagram of effort versus working position

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Results of simulations show that the proposed device practically balances perfectly the load at any working position. This means that in all working volume of the device, the operator does not need to exert any effort to suspend and manipulate the load. In addition to simulations, the proposed device is implemented and tested.

3.2. Developed prototype

The figure 11 shows a picture of the developed prototype. The prototype is constructed using steel tubes and strips. The level has at the load side a length of approximately 680mm and the working range is of approximately 60º. A gas spring that develops a force of 300N is used to generate the main counter balancing force. The device is designed to handle loads from approximately 30N to 55N. Fig.12 shows details of the correction mechanism. A potentiometer is used as the working position sensor. The rotation of the lever is amplified and transmitted by pulleys and a belt to the sensor shaft. After the constructing the prototype, the error map is measured.

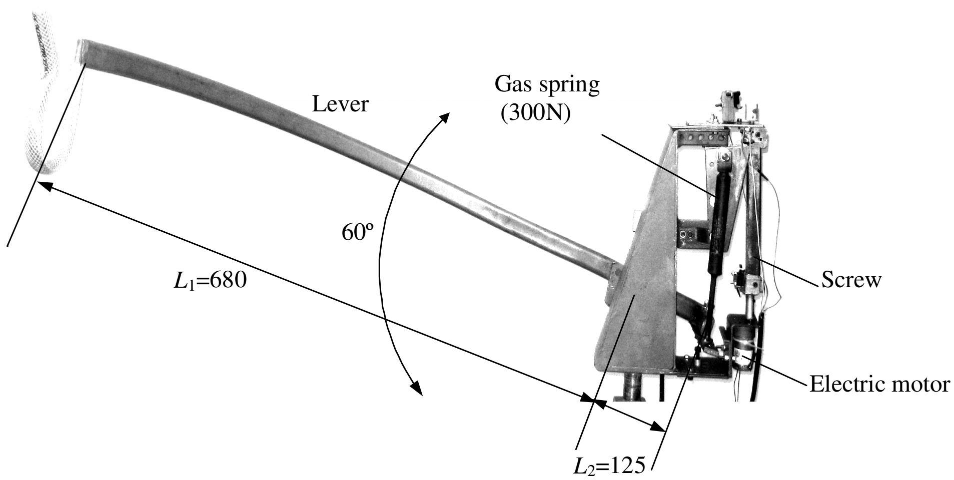

Figure 11 Prototype of proposed device

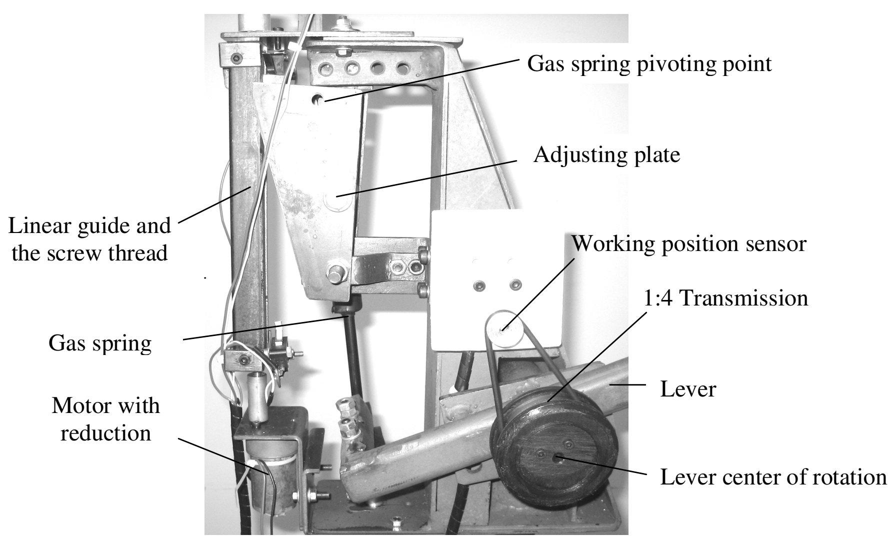

Figure 12 The correction mechanism and the working position sensor

3.3. Calibration

The purpose of the calibration is to build the error map, a map that correlates the working position of the lever and the correction to be made in the gas spring position, i.e., the correction necessary to balance a given load. To balance a different weight, a new error map must be inserted in the controller, because the angle between the gas spring and the arm of the lever changes with the variation of the weight, and the control system must to keep this angle constant in relation of the working position.

In the test, the calibration is made using a 5.5 kg weight. The calibration procedure consists on: a) first, move the load for a determined working position (α), b) second, the electric motor is switched manually, adjusting the gas spring position until the load is perfectly balanced and then, c) third, the number of turns necessary to correct the position is registered. This procedure is repeated for various working positions. Results are presented in Table 2. For comparison, simulated values are also mentioned. The working position is measure in volts, because the signal of working position sensor is given by the potentiometer. Results show that values very close to the theoretical one is obtained. Small discrepancies are verified but it is supposed that these occurred as consequence of differences between the parameters used in the simulation and the real value of the parameters. These results demonstrate the effectiveness of the compensation mechanism and of the architecture of the mechatronic load balancer.

Table 2. Errors map, obtain with simulation and calibration (5.5kg load).

Sensor reading (V)	Working position (rad)	No. of turns (experimental)	No. of turns (simulation)
6.2	0.52	57	51
5.7	0.41	41	37
5.1	0.29	33	28
4.6	0.17	19	15
4.0	0	7	0
3.5	– 0.12	18	11
2.9	– 0.17	23	21
2.4	– 0.29	38	31
1.8	– 0.41	45	43
1.3	– 0.52	55	48

4. CONCLUSIONS

This work presented a mechatronic concept for a device to balance a load enabling a human operator to manipulate loads with minimum effort. The proposed device is based in one of simplest mechanism possible to this purpose, a lever and a gas spring that generates the force necessary to balance the load. The load is not perfectly balanced in the working volume. Thus, instead adding a more complex mechanical system, a correction mechatronic mechanism is introduced. The effectiveness of the correction mechanism is demonstrated by simulations and experiments. By conceiving the device as a mechatronic system, it is possible to develop simpler solutions than strictly mechanical solution. Although the study plans the use of a PLC to control automatically the device, in this work, experiments are not conducted with the system in automatic operation. However, obtained results are enough to demonstrate the effectiveness of the solution. The remaining work to achieve automatic correction is simple. This will be done in near future.

5. ACKNOWLEDGEMENTS

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