A Power Assist Device for handling Heavy loads

Pablo Gonzalez de Santos, Elena Garcia, Javier F. Sarria, Roberto Ponticelli and Jesus Reviejo

Department of Automatic Control
Institute of Industrial Automation – CSIC
28500 Arganda del Rey, Madrid, Spain
pgds@iai.csic.es

Abstract:

Manipulation of heavy loads in industry is a main concern that produces low-back disorders in workers and a large number of accidents, especially in Small and Medium Enterprises. Human amplifiers and Power Assist Devices provide strength to operators, but they do not improve the position accuracy nor increase functionality in unusual situations by interacting with the user. The main idea behind resolving this problem is to augment the human capacity to lift and handle loads by using Power Assist Devices, while also enhancing the machines' capacities with properties which are not matched by the manipulation systems currently available. This paper presents a power–assists–device concept to handle very heavy loads with an accuracy of few millimeters, based on a system that features capabilities to co-operate with the operator in developing the required tasks and protecting him/her from injuries and accidents. Human-robot cooperation will be achieved using intuitive interfaces that incorporate advanced sensors and haptic and kinesthetic devices that allow for definition and/or learning and thus assist the completion of complex tasks which require, for example, the handling of heavy loads with high-precision positioning, the avoidance of obstacles and the negotiation of incidents of different kinds. This paper introduces the device structure and features and describes the main control characteristics.

1. INTRODUCTION

The need to handle heavy loads arises very frequently in an industrial environment, particularly in Small and Medium Enterprises (SME), where workers suffer a large number of accidents and injuries. These loads are sometimes sufficiently light for workers to lift them, but because they have to do so, on a very frequent basis, this can result in fatigue and, in the worst of cases, injury. According to the European Agency for Safety and Health at Work (OSHA, 2008), around 30% of European workers suffer back injuries caused by the physical effort involved in lifting and handling loads, repetitive movements or the need to maintain a particular posture. As a result, EU labour legislation is restricting the loads that can be directly handled by workers. This legislative trend, combined with safety at work recommendations, are now making it necessary for tools and handling support systems to be used whenever loads exceed legal limits.

Various tools to aid handling (Power-Assist Devices, PADs) have been designed and marketed with a view to solving this problem, using gravity compensation and load counter-weighting with limited degrees of freedom. These conventional devices are operated either directly by the operator or by means of very primitive interfaces, and while they have had a positive impact on working conditions for operators they have not improved the precision with which items can be positioned, or the way in which they can be guided, nor have they increased functionality in unusual situations or interaction with the user. Furthermore, their use is not intuitive, offering a poor reactive response and no inertia control. This means that the operators tends to have to move the load backwards and forwards over the intended position in a series of corrective moves, a circumstance which can lead to muscle fatigue and loss of concentration, which clearly alters working routines and, therefore, productivity.

Power-Assist Devices have been designed and marketed, based on passive movement mechanisms (Delnondedieu and Trocazz, 1995) and/or gravity-compensation elements. These simple systems really only help to support the weight of the object in question and lead to serious problems in terms of controlling inertia (decelerating or braking the load), following a particular trajectory or arriving at a relatively precise position.

In the mid-1990s, a group of engineers and researchers at Northwestern University, NU, (IL, USA) and the University of California at Berkeley, UCB, using specifications from the automotive industry and the OSHA (Occupational Safety and Health Administration, USA) suggested using computer-controlled technology to improve the capacities of people working with PADs. They coined the term "Intelligent Assist Devices" (IADs) (Book *et al.*, 1996) exhibiting very important potential features for power assistance, guidance and trajectory following and, above all, safety conditions in the workplace (Colgate and Peshkin, 2008; Surdilovic et al., 2003; Otani *et al.*, 1999; McGee and Swanson, 1999).

These devices combined concepts like "Human Enhancers" or "Human Power Amplifiers" (Kazerooni, 1995) with "collaborative robots" (Akella, *et al.*, 1998; Colgate *et al.*, 1996; Moore *et al.*, 2003). In the human enhancer concept developed by Kazerooni (UCB) (Kazerooni, 1995), a manipulator activated with the strength of an operator increases or amplifies his or her capacity to lift or handle loads. With the concept of the collaborative robot, invented by Colgate and Peshkin at NU (Leite *et al.*, 2006; Moore *et al.,* 2003), the main function is to define a virtual surface (Leite *et al.*, 2006; Moore *et al.,* 2003), over which the load can be moved. When it is working, the operator directly applies his or her own force to move the load, whose movement is restricted within the area and cannot move outside it as a result of the device. This area can be reduced to a path or extended to a wider space (channels or funnels, for example). Similarly, "attraction points" can be defined, which lead the device towards them without the need for any direct action from the operator. This collaborative robot, also known as a "cobot" (collaborative robot) (Akella, *et al.*, 1998; Colgate *et al.*, 1996; Moore *et al.,* 2003; Peshkin et al., 2001) can become a passive and therefore safe system for the operator, since by using the handling device the control system redirects the operator's force instead producing the movement directly.

This paper introduces a new PAD devoted to the accurate handle of heavy loads. Accurate motion and heavy load handling are antagonist features. The first is provided by electric actuator technology, which provides a low torque/weight ratio; the later is mainly provided by hydraulic devices, that provides low accuracy. The new PAD introduced herein uses the accuracy provided by modern AC motor technology with the design of a new manipulator structure to reduce the effects of the low torque/weight ratio provided by these actuators.

This paper is organised as follows. Section 2 introduces the main system requirements. Section 3 presents the mechanical structure of the PAD arm. Section 4 sketches the PAD wrist structure and, finally, Section 5 reports some conclusions.

2. SYSTEM REQUIREMENTS AND AIMS

The technical and scientific aims of this development are to carry out research into systems for human augmentation devices or power-assist devices, PADs, which will involve the design and development of an intelligent device to assist the handling of heavy loads of up to 75 kg with an accuracy of ±2 mm and an arm length of about 2 meters. The basic objectives are to guarantee precision placing and guidance in the face of any kind of contingency, while complying with the regulations governing operative safety, in a wide range of applications including the automotive industry, the assembly of heavy and/or bulky pieces, handling in the food industry, moving patients in the health sector, rehabilitation, etc.

The specific scientific and technical aims of this work are as follows:

1. The design and manufacturing of a new mechanical structure for a power-assist device.
2. The appropriate use of sensors on the power-assist device to allow interaction with the operator and his/her surroundings.
3. The implementation of a distributed control system that allows the power-assist device to interact with an operator.
4. The design and implementation of a multifunctional human-machine interface that allows the device to be handled and guided both intuitively and safely.
5. The design of algorithms allowing safe, stable and transparent haptic control of interaction of high-force device and human.
6. The design of a supervision and control architecture for the definition, correction and implementation of virtual surfaces and volumes.

This power-assist device could be sufficiently versatile and safe to interact directly, through physical contact, with an operator and the real/virtual environment.

3. MANIPULATOR STRUCTURE

The mechanical structure of the Power Assists Device presented herein is defined by its workspace and payload.

3.1 Manipulator Workspace

The manipulator must exhibit an arm extension of about 2 m; therefore, its workspace could be a two-meter-radius cylinder. The requirement about the capability of human-machine interaction fulfilling with governing laws (ergonomic and safety) recommends to fixed the workspace height between 0.25 m and 1.5 m over the ground (see Fig. 1 for manipulator workspace dimensions and shape).

3.2 Payload Handling

The heavy payload the manipulator must handled (about 75 Kg), along with the large dimensions of its workspace (two-meter radius), is the most demanding feature. To decrease static joint torques, the use of a Cartesian or SCARA mechanical structure is the normal consideration. It is well known that in these configurations the own structure supports the payload without applying joint torques. Additionally, the SCARA structure is ordinarily faster and easier to build, thus, it has been considered as the most adequate structure for our purposes.

The SCARA structure provides, basically, two horizontal degrees of freedom (DoF). The main arm structure should provide at least three DoF –a wrist would provide up to three additional DoF– therefore, we still need to provide a vertical motion of the load. There are different possible configurations to provide the vertical motion in a SCARA structure. The most common solution consists in using a vertical, prismatic joint in either the first joint or in the third joint. The latter configuration is the typical one used in SCARA industrial manipulators to carry light payload. The former is used in industrial and service SCARA manipulators to handle heavy loads (Gonzalez de Santos *et al.*, 2008). Technically speaking, this is an easy solution; however, the main SCARA links move inside the workspace where the operator is also moving and to avoid dangerous situations for the operator the SCARA links are placed overhead the operator (see Fig.1).

This configuration can still be used with a vertical, prismatic joint, but the solution presents a very big sweeping volumes. One simple and efficient solution used by many industrial assist devices (Dalmec, 2008) relies on a parallelogram structure powered vertically through a rotary joint (see Fig. 2). This configuration is very easy to implement but exhibit a very hard shortcoming: if it is used as the first manipulator joint (see Fig. 2), then it must exert a very large torque to drive the payload plus the actuator masses of the rest of the joints.

One new solution, which is the main contribution of this paper, is to use a parallelogram structure as the third joint as indicated in Fig. 1. In this way, joint 3 must exert a torque to move vertically the payload plus the wrist actuator masses. The mass of the actuator 2 is directly supported by the SCARA structure. This solution gives the same workspace than traditional solution but it needs to exert lower torques allowing better features (higher load velocities and accelerations, and light-weighter motors and gearboxes). Figure 3 sketches the basic structures for both (a) traditional and (b) new power assist device configurations. In both configurations motors 1 and 3 do not need to exert any torque to support the load, m. In the first configuration motor 2a supports the vertical load and must exert a static torque:

$$\tau_{2a} = m_3 g (D\text{-}d) + mgD \tag{1}$$

where m_3, D and d are defined in Fig. 3, and g is the gravity.

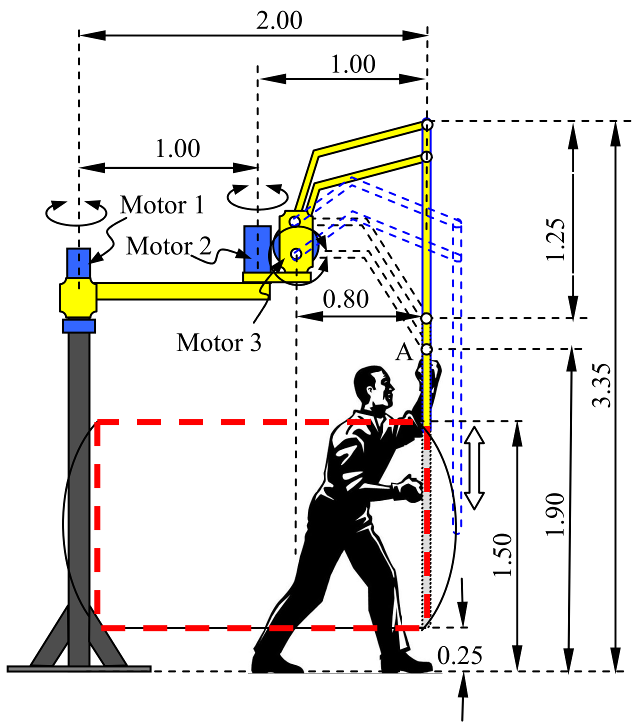


Fig. 1. Sketch of the main structure and dimensions of the power assists device (Units in meters).

In the second configuration, motors 1 and 3 again do not need to support the load, which is moved vertically by motor 2b that needs to exert a static torque:

$$\tau_{2b} = mgd \tag{2}$$

If the link lengths are equal, as most of the manipulators in industry, then:

$$D=2d \tag{3}$$

and equations (1) and (2) yield:

$$\tau_{2b} = \tau_{2a} - (m_3 + m) gd \tag{4}$$

Therefore, our new configuration decreases the static torque required to move the load vertically in about $\Delta\tau = -(m_3+m)gd$ Nm.

Figure 4 illustrates the final structure designed taking into account the manipulator dimensions given in Fig. 1.

4. WRIST STRUCTURE

The wrist of the PAD basically consists of three DOF with the joint rotation axes crossing at point O_0 (see Fig. 5). The yaw joint rotates about the axis $\boldsymbol{x_0}$ and produces the horizontal motion of the load and it does not need to exert a torque to support the load. The pith, θ_1 axis (rotation about $\mathbf{z_0}$), and the roll, θ_2 axis (rotation about z_1), need to exert a given torque to support the *COG* of the load located at position $(L_2, L_3, 0)^T$ with respect to the reference frame (O_2, x_2, y_2, z_2). T indicates the transpose vector.

Fig, 5 shows the reference frames and the parameters of the wrist angles following the convention of Denavit-Hartenberg. The homogeneous matrices ${}^{j}\mathbf{A}_{i}$ that transform a vector in the system i into the system j are given by:

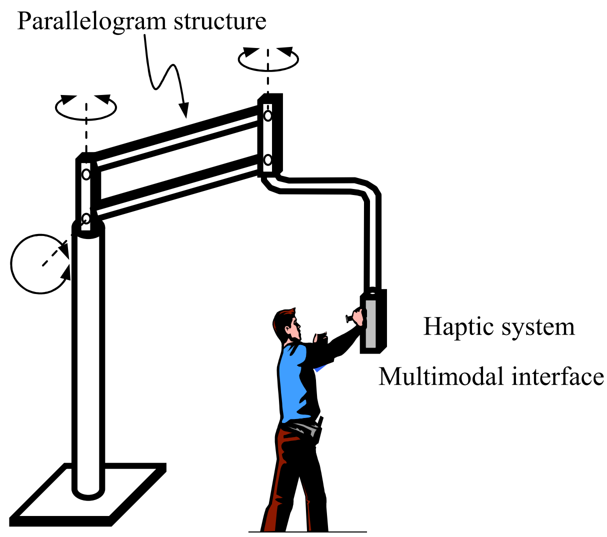


Fig. 2. Typical use of the parallelogram structure

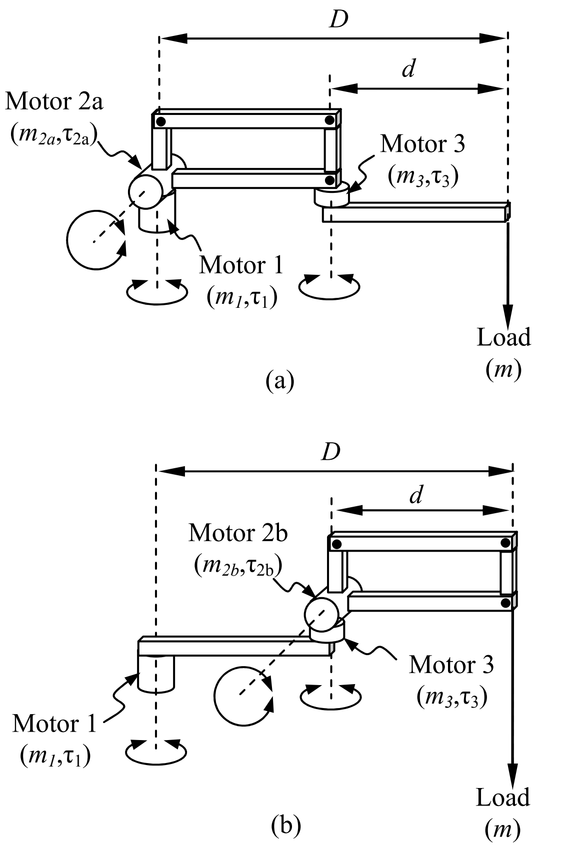


Fig. 3. (a) Traditional and (b) new PAD configuration

$$
{}^{0}\mathbf{A}_{1} = \begin{pmatrix} \cos\theta_1 & 0 & -\sin\theta_1 & 0 \\ \sin\theta_1 & 0 & \cos\theta_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{5}
$$

and

$$
{}^{1}\mathbf{A}_{2} = \begin{pmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{6}
$$

$$
{}^{0}\mathbf{A}_{2} = {}^{0}\mathbf{A}_{1}\,{}^{1}\mathbf{A}_{2} \tag{7}
$$

Thus, the vector $\overline{\mathrm{p}}_2$ that determines the position of the *COG* in the reference frame (O_2, x_2, y_2, z_2) is given by (see Fig. 5):

$$
\overline{\mathrm{p}}_2 = (L_2 \quad L_3 \quad 0 \quad 1)^{\mathrm{T}} \tag{8}
$$

and its position, $\overline{\mathrm{p}}_0$, in the reference frame (O_0, x_0, y_0, z_0) is given by

$$
\overline{\mathrm{p}}_0 = {}^{0}\mathbf{A}_{2}\overline{\mathrm{p}}_2 \tag{9}
$$

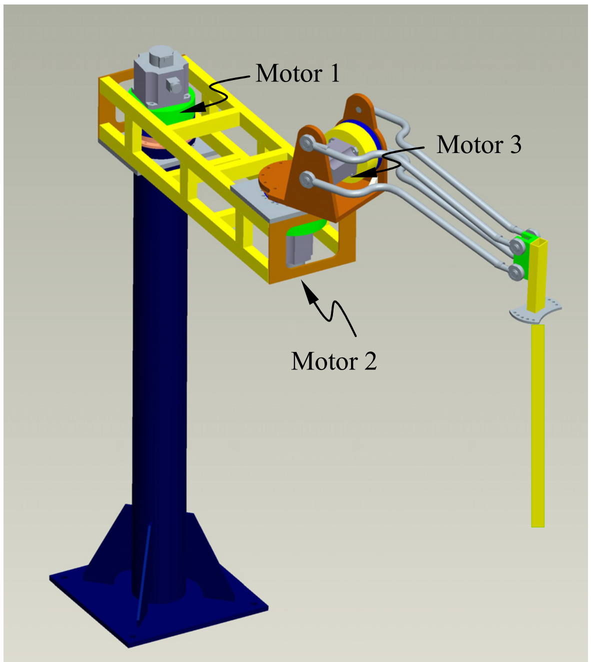


Fig. 4. Design of the Power Assist Device Arm

In general, the torque of a force, $\overline{\mathrm{F}}$, about an axis, $\overline{\mathrm{u}}$, is defined as the projection on $\overline{\mathrm{u}}$ of the torque

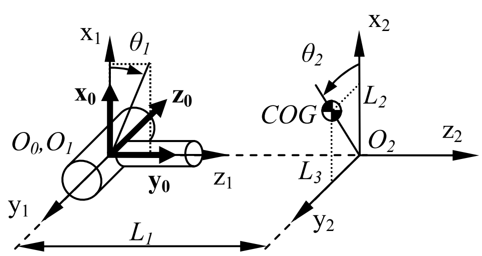
$$
\overline{\tau} = \overline{\mathrm{r}} \times \overline{\mathrm{F}} \tag{10}
$$

where $\overline{\mathrm{F}}$ is the force, $\overline{\mathrm{r}}$ is a vector from any point in the rotation axis $\overline{\mathrm{u}}$ to the point of application of the force $\overline{\mathrm{F}}$, and $\times$ represents the vector cross product.

The projection of a vector $\overline{\tau}$ on a vector $\overline{\mathrm{q}}$ is given by the dot product

$$
\eta = \overline{\tau}^{\mathrm{T}} \cdot \overline{\mathrm{q}} \tag{11}
$$

thus, the torque produced by the mass, *m*, (i.e. $F = -mg$) acting on the *COG* about the axis z_0 is given by



i	a_i	d_i	α_i	θ_i
1	0	0	$3\pi/2$	θ_1
2	0	L_1	0	θ_2

Fig. 5. Reference systems and Denavit-Hartenberg parameters for the wrist model

$$\tau_{\text{pitch}} = \left(\bar{p}_0 \times \left(-mg \quad 0 \quad 0 \right)^{T} \right)^{T} \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad (12)$$

which is known as the pitch torque, and the torque around axis ${}^{0}z_{1}$, which is known as the roll torque, is

$$\tau_{\text{roll}} = \left(\bar{p}_0 \times \left(-mg \quad 0 \quad 0 \right)^{T} \right)^{T} \cdot {}^{0}z_{1} \qquad (13)$$

where ${}^{0}z_{1}$ is the vector

$${}^{1}z_{1} = \left(0 \quad 0 \quad 1 \right)^{T} \qquad (14)$$

in the reference system (O_0, x_0, y_0, z_0). That is

$${}^{0}z_{1} = \begin{pmatrix} \tilde{z}_{11} \\ \tilde{z}_{21} \\ \tilde{z}_{31} \end{pmatrix} \qquad (15)$$

where

$$\begin{pmatrix} \tilde{z}_{11} \\ \tilde{z}_{21} \\ \tilde{z}_{31} \\ 1 \end{pmatrix} = {}^{0}\mathbf{A}_{1} \begin{pmatrix} {}^{1}z_{1} \\ 1 \end{pmatrix} \qquad (16)$$

Note that ${}^{0}\mathbf{A}_{1}$ is a (4×4) matrix while ${}^{1}z_{1}$ is a (3×1) vector. Figure 6 plots the pitch and roll torques (given by (12) and (13), respectively) exerted by a mass of 75 kg located at the point defined by (see Fig. 5 for geometric definitions):

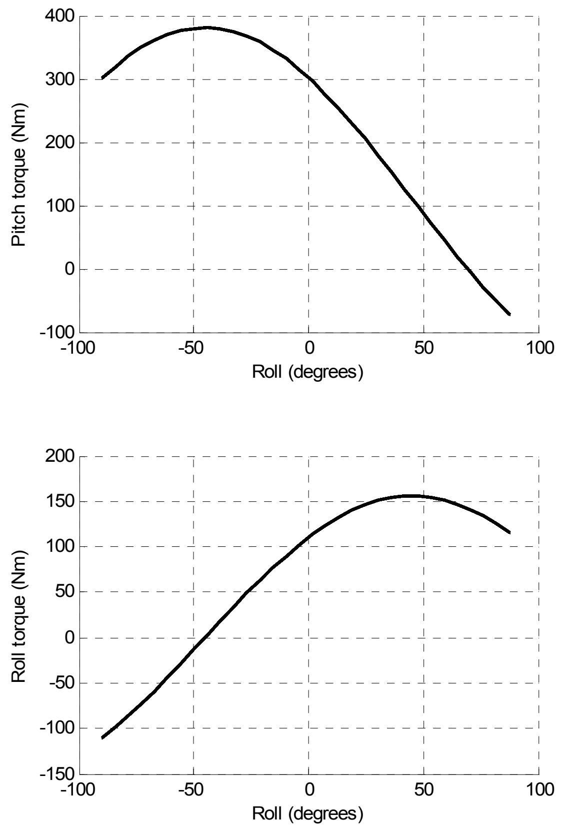


Fig. 6. Pitch and roll torques in the wrist joints as a function of the roll angle when the pitch angle is 60°

$$L_1 = 0.3 \text{ m}, \; L_2 = 0.3 \text{ m}, \; L_3 = 0.3 \text{ m}, \qquad (17)$$

when the roll angles vary in $\left(-\pi/2, \pi/2\right)$ and the pitch angle is 60°. The maximum torques reached in this example are indicated in Table 1, and must be exerted directly for two independent motors in a configuration in which a motor only drives a joint. However, if the motors are coupled mechanically through a differential system, for instance, the maximum torques can be reduced as presented below.

Our differential system is configured around a typical three-conical-pinion system (see Fig. 7). Two motors rotate two fixed conical pinions placed opposite to each other. A third conical pinion is forced to rotate (a) about the common axis of the fixed pinions, (b) about its own axis or (c) a combination of rotations (a) and (b), depending on the motor's direction of motion and speed. With this configuration the motors work at the same time providing the required torques acting simultaneously, i.e., each motor provides a fraction of the required torque and power to move the load, while by using single motor joints each motor must provide the required independent torque.

Table 1. Maximum torques in wrist

Maximum torque	(Nm)
Pitch	380.66
Roll	155.92
Joint 1	211.25
Joint 2	211.14

The differential system satisfies the following relationships:

$$\tau_1 = \frac{\tau_{\text{pitch}} + \tau_{\text{roll}}}{2} \qquad \tau_2 = \frac{\tau_{\text{pitch}} - \tau_{\text{roll}}}{2} \qquad (18)$$

where τ_i defines the torque in joint *i*. These torques are plotted in Fig. 8 for the same pitch and roll values than in previous example.

The maximum values of these torques are also indicated in Table 1. Note that the maximum joint torque using a differential system is 211.25 Nm while the maximum pitch torque is 380.66 Nm, this represents a reduction of the maximum torque of about 35.5%.

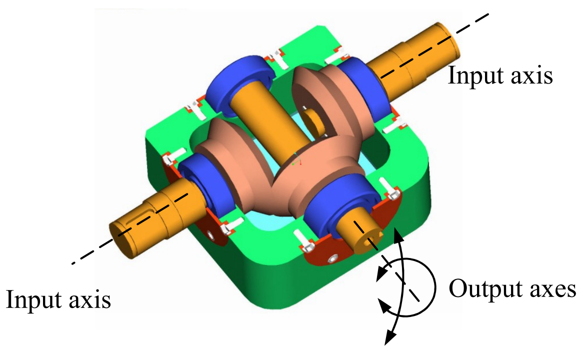


Fig. 7. Differential system of the wrist

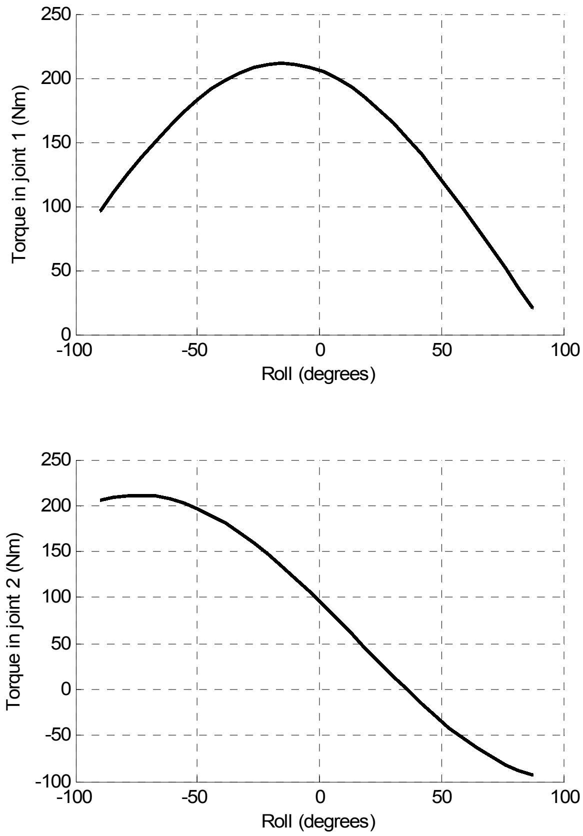


Fig. 8. Joint torques in a differential wrist as a function of the roll angle when the pitch angle is 60°

5. CONCLUSIONS

This paper presents a design intended to test a new structure for Power Assist Devices. This structure is divided into arm and wrist and both are designed to diminish the required torques as much as possible. The arm relies on a mixture of SCARA type manipulator with a vertical joint based on a parallel structure, while the wrist is based on a typical differential system capable of decreasing the maximum torques required by a joint independent system. The PAD will be endowed with a 6 DOF force/torque sensor to allow the operator to interact with the manipulator in a friendly and safe manner improving operator accuracy and eliminating the operator musculoskeletal disorders for carrying heavy loads or for handling low loads but repetitively. This is the future work to be attained.

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