Abstract:

Purpose – This paper introduces a new manipulator structure to configure power-assist devices in order to protect operators from musculoskeletal disorders. The mechanical structure and the control system are presented, along with their main features.

Design/methodology/approach – The new structure is designed under the criterion of minimizing the torques required for handling payloads of up to 75 kg in an easily controlled system.

Findings – A new structure is provided, based on electrical AC motors and capable of handling high payloads yet exerting low motor torque.

Originality/value – The application of the criterion of minimizing the required torques to handle heavy payloads produced a new manipulator structure. This structure is patent protected.

Keywords – Robotics, Power-assist devices, Easy handling.

Paper type – Research paper

1. Introduction

Handling of heavy loads is a main concern in industry. Load mishandling causes lower back disorders in workers and a large number of accidents, especially in small and medium enterprises, where workers are liable to undergo more accidents and injuries. Loads are sometimes light enough for workers to lift, but because they have to be lifted very frequently, fatigue and, in the worst of cases, injury may easily result. According to the European Agency for Safety and Health at Work (OSHA, 2009), 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. In the naval industry, for example, there is now a 25-kg
limit on the loads that can be directly handled by one operator, and the sectors that support the construction industry are reducing the weight of their products (such as bags of cement). This legislative trend, combined with safety-at-work recommendations, is now making it necessary for tools and handling-support systems to be used whenever loads exceed legal limits.

Various tools to aid in 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 items can be guided, nor have they increased functionality in unusual situations or interaction with the user. Furthermore, their use is not intuitive; they offer but poor reactive response and no inertia control. This means that the operator tends to have to move the load back and forth over the intended position in a series of corrective moves, a circumstance that 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 (Delnondiedieu and Trocagg, 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) to describe mechanisms displaying some very important potential features for power assistance, guidance, trajectory following and, above all, safety conditions in the workplace (Colgate and Peshkin, 2008; Peshkin and Colgate, 1999; 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 over which the load can be moved. When the robot 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; Peshkin and Colgate, 1999; Colgate et al., 1996; Moore et al., 2003; Peshkin et al., 2001), can become a passive and therefore safe system for the operator: When the handling device is used, the operator does not produce the movement directly; rather, the control system redirects the operator’s force.

This paper presents a power-assist device concept to handle very heavy loads with an accuracy of a few millimetres, based on a system that features capabilities enabling the device to cooperate with the operator in performing the required tasks and to protect the operator from injuries and accidents. Human/robot cooperation is achieved using intuitive interfaces that incorporate advanced sensors and haptic and kinaesthetic devices that allow for definition and/or learning and thus assist in the completion of complex tasks that require, for example, the handling of heavy loads with high-precision positioning, the avoidance of obstacles and the negotiation of different kinds of incidents. 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 the actuators.

This paper is organized as follows. Section 2 introduces the main system requirements. Section 3 presents the mechanical structure of the PAD, divided into arm and wrist. Some additional features, such as the operator/machine interface and the controller, are presented in Section 4. Finally, Section 5 reports some conclusions.

2. Main aims and system requirements

The technical and scientific aims of the development work at issue are to carry out long-term 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 in the handling of heavy loads of up to 75 kg with an accuracy of ±2 mm and an arm length of about two metres. The basic objectives are to guarantee precision placing and guidance in the face of any kind of contingency, while complying with the regulations governing operating safety, in a wide range of applications including the automotive industry, the assembly of heavy and/or bulky parts, handling in the food industry, the movement of patients in the health sector, rehabilitation, etc.

The specific scientific and technical objectives of this long-term work are as follows:

1. The design and manufacturing of a new mechanical structure for a power-assist device capable of covering a large number of applications.
2. The appropriate use of sensors on the power-assist device to allow cognitive, haptic and kinaesthetic interaction between the operator and his/her surroundings.
3. The implementation of a distributed control system that allows for data to be received from the sensors and provides the relevant control coordination to allow the power-assist device to interact with an operator and a real/virtual environment with high stability and performance.
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 enabling safe, stable, transparent haptic control of the interaction between 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 (pipes, funnels) that will assist and oversee the guidance and control of the system by the operator, offering precision and reliability for the application and safety for the operator.

This power-assist device could be sufficiently versatile and safe to interact directly, through physical contact, with an operator and the real/virtual environment. The work presented herein relies on the first technical and scientific objective presented above.

3. Mechanical structure of the PAD

The mechanical structure of the power-assist device presented herein is divided into two substructures: the arm structure and the wrist structure. The arm structure is
determined by two features, workspace and payload, while the wrist structure is dictated by the minimization of the requested joint torques. The following sections present the solution found for the manipulator structure in order to implement the required features.

3.1. PAD arm structure

3.1.1. PAD workspace

The PAD must exhibit an arm extension of about two metres; therefore, its workspace could be a cylinder with a radius of two metres. Under ergonomic and safety laws concerning the capability of human/machine interaction, the recommended workspace height is between 0.25 metres and 1.5 metres above the ground (see Fig. 1 for manipulator workspace dimensions and shape).

3.1.2. Payload handling

The heavy payload the manipulator must handle (about 75 kg) and the large dimensions of the manipulator’s workspace (two-meter radius) conform the most demanding feature. To reduce static joint torques, use of a Cartesian or SCARA mechanical structure is normally considered; in such configurations, the structure itself supports the payload without applying joint torques. Additionally, the SCARA structure is ordinarily faster and easier to build, and it was accordingly considered the best

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Fig. 1. Sketch of the main structure and dimensions of the power-assist device (Units in metres).
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, some means of providing vertical motion of the load was still needed. There are different possible configurations for providing vertical motion in a SCARA structure. The most common solution consists in using a vertical prismatic joint in either the first joint or the third joint. The latter configuration is what is typically used in industrial SCARA manipulators to carry light payloads. The former is used in industrial and service SCARA manipulators to handle heavy loads (Gonzalez de Santos et al., 2003). Technically speaking, this is an easy solution; however, the main SCARA links move inside the workspace where the operator too is moving. So, to avoid dangerous situations for the operator, the SCARA links were placed overhead (see Fig. 1).

This configuration can still be used as a vertical prismatic joint, but the solution presents a very big volume. One simple and efficient solution used by many industrial assist devices (Dalmec, 2009) relies on a parallelogram structure powered vertically through a rotary joint (see Fig. 2). This configuration is very easy to implement but does exhibit a serious shortcoming: If it is used as the first manipulator joint, 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. Thus, joint 3 must exert a torque to move the payload plus the wrist actuator mass vertically. The mass of actuator 2 is directly supported by the SCARA structure. This solution gives the same workspace as the traditional solution, but it needs to exert lower torques, thus affording superior features (higher load velocities and accelerations, and lighter-weight motors and gearboxes). Figure 3 illustrates the basic structures for both (a) the traditional and (b) the 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:

\[
\tau_{2a} = m_3 g (D-d) + mgD
\]  

(1)

where \( g \) is gravity, \( m_3 \) is the mass of motor 3 and \( D \) and \( d \) are geometric parameters defined in Fig. 3.
In the second configuration, again motors 1 and 3 do not need to support the load, which is moved vertically by motor 2b, which needs to exert a static torque:

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

(2)

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

$$D = 2d$$

(3)

and equations (1) and (2) yield:

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

(4)

Therefore, our new configuration reduces the static torque required to move the load vertically by

$$\Delta \tau = -(m_3 + m)gd \text{ Nm.}$$

Figure 4 illustrates the final arm structure, designed taking into account the manipulator dimensions given in Fig. 1. Note that the motors of the arm substructure are placed in positions that do not load the arm joints.

3.2. PAD Wrist Structure

The wrist basically consists of three DOF with the joint rotation axes crossing at point $O_0$ (see Fig. 5). The yaw joint rotates about axis $x_0$ and produces the horizontal motion of the load, and it does not need to exert any torque to support the load. The pitch, $\theta_1$ (rotation about axis $z_0$), and the roll, $\theta_2$ (rotation about axis $z_2$), need to exert a
given torque to support the COG of the load located at position \((L_2, L_3, 0)\) with respect to the reference frame \((O_2, x_2, y_2, z_2)\). \(T\) indicates the transpose vector.

Figure 5 shows the frames of reference and the parameters of the wrist angles following the Denavit-Hartenberg convention. Following the homogeneous matrix \(^{j}A_{i}\) that transforms a vector in system \(i\) into system \(j\), we get:

\[
^{0}A_{1} = \begin{pmatrix}
\cos \theta_1 & 0 & -\sin \theta_1 & 0 \\
\sin \theta_1 & 0 & \cos \theta_1 & 0 \\
0 & -1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\]

\[
^{1}A_{2} = \begin{pmatrix}
\cos \theta_2 & -\sin \theta_2 & 0 & 0 \\
\sin \theta_2 & \cos \theta_2 & 0 & 0 \\
0 & 0 & 1 & L_i \\
0 & 0 & 0 & 1
\end{pmatrix}
\]
Thus, vector $\mathbf{p}_2$, which determines the position of the COG in the reference frame $(O_2, x_2, y_2, z_2)$, is given by (see Fig. 5):

$$\mathbf{p}_2 = (L_2, L_j, 0, 1)^T$$

(8)

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

$$\mathbf{p}_0 = ^0\mathbf{A}_2\mathbf{p}_2$$

(9)

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

$$\mathbf{\tau} = \mathbf{\tau} \times \mathbf{F}$$

(10)

where $\mathbf{F}$ is the force, $\mathbf{\tau}$ is the vector from any point on rotation axis $\mathbf{u}$ to the point of application of force $\mathbf{F}$, and $\times$ represents the vector cross product.

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

$$\mathbf{\tau} \cdot \mathbf{q}$$
Thus, the torque produced by mass $m$ (i.e., $F = -mg$) acting on the COG about axis $\tau_0$ is given by

$$\tau_{\text{pitch}} = \left[ \mathbf{p}_0 \times (-mg) \right]^T \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

which is known as the pitch torque, and the torque around axis $\mathbf{0z}_1$, which is known as the roll torque, is

$$\tau_{\text{roll}} = \left[ \mathbf{p}_0 \times (-mg) \right]^T \cdot \mathbf{0z}_1$$

where $\mathbf{0z}_i$ is the vector

$$\mathbf{0z}_i = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Fig. 5. Reference systems and Denavit-Hartenberg parameters for the wrist
in the reference system \((O_0, x_0, y_0, z_0)\). That is

\[
\underline{\tau}_i = \begin{pmatrix}
\tilde{z}_{11} \\
\tilde{z}_{21} \\
\tilde{z}_{31} \\
1
\end{pmatrix}
\]

where

\[
\begin{pmatrix}
\tilde{z}_{11} \\
\tilde{z}_{21} \\
\tilde{z}_{31} \\
1
\end{pmatrix} = {}^0A_i \begin{pmatrix}
\underline{\tau}_i \\
1
\end{pmatrix}
\]

Note that \( {}^0A_i \) is a \((4 \times 4)\) matrix, while \( \underline{\tau}_i \) is a \((3 \times 1)\) vector.

Figure 6 plots the pitch and roll torques (computed with (12) and (13), respectively) exerted by a mass of 75 kg located at the point defined by (see Fig. 5 for geometric definitions):

\[
L_1 = 0.3 \text{ m}, \ L_2 = 0.3 \text{ m}, \ L_3 = 0.3 \text{ m}
\]

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

Our differential system is configured around a typical three-conical-pinion system. Two motors turn 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. 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, when single motor joints are used, each motor must provide the required independent torque (see Figure 7).

The differential system satisfies the following relationships:

\[
\begin{align*}
\tau_1 &= \frac{T_{\text{pitch}} + T_{\text{roll}}}{2} \\
\tau_2 &= \frac{T_{\text{pitch}} - T_{\text{roll}}}{2}
\end{align*}
\]

where \( \tau_i \) defines the torque in joint \( i \).

The torques in joints 1 and 2 for the same example presented above are plotted in Fig. 8. The maximum values of these torques are also indicated in Table 1. The maximum joint torque may be observed to be 246.63 Nm, while the maximum pitch

Fig. 6. Pitch and roll torques in the wrist joints as a function of the pitch and roll
torque is 382.14 Nm. This means the maximum torque has been reduced by about 35.5%.

Figures 4 and 9 show the position of the wrist joints and motors.

4. Additional features

4.1. Operator/machine interaction

The manipulation system is intended to share its workspace with a human operator (see Fig.’s 1 and 2); therefore, two interaction modes might be considered. The first is the workspace interaction, where safety and health regulations must be fulfilled. A manipulator substructure that moves horizontally does not interact with the operator. The lowest interacting manipulator substructure point is 1.9 metres above the ground (Point A in Fig. 1). The vertical substructure is a small-diameter rod that interacts with the operator in horizontal motions. This spatial interaction is minimum, because the vertical substructure moves with the operator, who handles an interaction device to move the manipulator to the required point. This action to position the manipulator is the second kind of interaction, which relies on a haptic system that consists of a 6-DoF force sensor that provides three forces and three torques. This interface allows the

<table>
<thead>
<tr>
<th>Link joints (m)</th>
<th>Column</th>
<th>1.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>First link</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Second link</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Third link (parallelogram)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Extensor</td>
<td></td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 2. Electrical and mechanical features of the PAD

<table>
<thead>
<tr>
<th>Joint</th>
<th>Range</th>
<th>Motor (AC Mitsubishi)</th>
<th>Reducer (Harmonic Drive)</th>
<th>Type</th>
<th>Power</th>
<th>Type</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>±170°</td>
<td>HF-SP202B 2 kW</td>
<td>CPU-58A-160-M 100:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>±170°</td>
<td>HF-SP202B 2 kW</td>
<td>CPU-58A-160-M 100:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0° to -78°</td>
<td>HF-SP152B 1.5 kW</td>
<td>CPU-50A-160-M 160:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>±170°</td>
<td>HF-KP43B 400 W</td>
<td>CPU-32A-80MM 80:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>±170°</td>
<td>HF-KP43B 400 W</td>
<td>CPU-32A-80MM 80:1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>±170°</td>
<td>HF-KP43B 400 W</td>
<td>CPU-32A-80MM 80:1</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
operator to start/stop and guide the PAD as well as to define several operating modes, using very few switches and buttons. This device can interpret the manoeuvres of the operator to guide the PAD.

4.2. Control system

The joint actuators are AC motors controlled directly by AC drivers. These drivers are commanded by commercial 3-axis PID controlling boards. An industrial PCI-bus-based computer coordinates all I/O boards and controllers and also communicates with the operator interface, which relies on a haptic system, as mentioned above. The control algorithms run on the QNX operating system, which provides real-time multitasking features.

The electric and electronic system is fully integrated into the PAD’s structure. This arrangement allows the drivers to be placed close to the actuators, thus avoiding the need for long electrical cables and tethers. In addition, there is no control cabinet near the PAD workspace.

Figure 9 shows what the PAD looks like. The location of the drivers and the control computer are shown. Table 2 summarizes the main mechanical and electrical features of the PAD.

![Differential system of the wrist](image)

Fig. 7. Differential system of the wrist
Fig. 8. Wrist joint torques as a function of the wrist pitch and roll angles
5. Conclusions

The work presented herein is part of a long-term research project devoted to configuring a manipulator for helping operators handle heavy loads, thus preventing musculoskeletal disorders. This article focuses on the design of the manipulator structure, and it affords a preview of some general features.

The design focuses on reducing the required joint torques in order to handle the heaviest possible payloads. Thus, the manipulator is based on electric actuators characterized by their low torque/weight ratio.

The main result is a new manipulator arm structure that consists of a mixture of a SCARA manipulator and a parallelogram structure that allows the operator to move inside its workspace. The wrist structure is based on a differential system that allows two motors to provide the required torque in a collaborative way. A detailed analysis of the wrist mechanism is provided, showing how joint torques are accurately determined. Some additional features of the PAD, addressing the issues of robot guidance and control, are given in Section 4.

Work is ongoing to provide the PAD with the sensors and interfaces required to configure an intelligent power-assist device (IPAD).

ACKNOWLEDGEMENT

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Figure 9. PAD prototype
REFERENCES


