Weight-Perception-Based Novel Control for Cooperative Lifting of Objects with a Power Assist Robot by Two Humans

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Abstract—The objective was to design and implement a weight-perception-based novel control strategy to improve performances when lifting objects with a power assist system by two humans cooperatively. We developed a 1-DOF power assist system for lifting objects. We hypothesized that weight perception due to inertia might be different from that due to gravity when lifting an object with power-assist because the perceived weight is different from the actual weight. The system was simulated and two humans cooperatively lifted objects with it. We critically analyzed weight perception, load forces and motion features. We found that the robot reduced the perceived weights of the cooperatively lifted objects to 25% of the actual weights and the applied load forces were 8 times larger than the actually required load forces. Excessive load forces resulted in excessive accelerations that jeopardized system performances. Then we implemented a novel control scheme based on human features that reduced excessive load forces and accelerations and thus enhanced performances in terms of maneuverability, safety etc. The findings may be used to develop power assist robots for manipulating heavy objects in industries that may augment human’s abilities and skills and may improve interactions between robots and humans.

I. INTRODUCTION

POWER assist robots assist humans to perform tasks by augmenting human’s abilities and skills. This type robot was first conceived in early 1960s with the invention of “Man-amplifier” and “Hardiman”[1]. However, the progress of research on this potential field is not satisfactory. Power assist robots are now confined to a few applications such as healthcare, rehabilitation, care for the elderly etc. [2]-[4]. We think that manipulating heavy objects in industries is another potential field of power-assist application. Manual manipulation of heavy objects is very tedious, causes health problems (e.g., back pain, injuries) to humans and restricts work efficiency [5]. On the contrary, autonomous systems do not provide required flexibility in object manipulation [6]. Hence, we argue that suitable power assist robots may be conveniently and efficiently used for handling heavy objects in industries such as forestry, mining, construction, manufacturing, transport and logistics, military activities, disaster and rescue operations etc. However, such robots are not available in practices in industries.

Few power assist systems are available for other applications e.g., slide doors for automobiles [7], lifting baby carriage [8], agricultural jobs [9], hydraulic assist for automobiles [10], bicycle [11], manufacturing [12], sports training [13], and so forth. However, suitable power assist systems for manipulating heavy objects are not usually seen.

A few power assist devices are available for handling objects [14]-[19]. However, we think that these are not suitable for lifting heavy objects in industries because they are not sufficiently safe, natural, and human-friendly. A power assist robot reduces the perceived weight of an object lifted with it [1], and hence the manipulative forces required to lift the object with power-assist should be lower than that required to lift the object manually. However, the human cannot correctly perceive the weight of the object before lifting it with the robot and eventually applies excessive load force (vertical lifting force), which results in sudden increase in acceleration, fearfulness of the user, lack of stability and maneuverability, injuries, fatal accidents etc. However, the existing systems do not consider weight perception issue.

We assume that appropriate power assist robots in industries for manipulating heavy objects are not found and their interactions with users are unsatisfactory because (i) specialized power assist robots for handling heavy objects have not been developed yet, and (ii) the conventional power-assist controls do not consider human characteristics such as weight perception, load forces and motion features.

Again, it is seen in industries that workers employ one or two hands to manipulate objects and sometimes two or more workers manipulate objects cooperatively. Workers decide these grasping and manipulation schemes on the basis of object’s physical features such as size, mass, shape etc. as well as of task requirements [20]-[22]. We assume that weight perception, load forces and object motions for one manipulation scheme may be different from that for others, and these differences may affect the control. We also assume that, out of three manipulation schemes (unimanual, bimanual, cooperative), the cooperative scheme may be the most beneficial because this scheme may provide some advantages over others in terms of perceived weights and load forces [20]. Again, cooperative scheme may be the suitable when manipulating large size, intricate shape objects. Few works addressed manipulation of a single object with a robot by a single human [14]-[19]. Cooperative manipulation of a single object by two robots was also studied [23]. Handling an object by two hands of a human was investigated [21]. However, cooperative manipulation of an object with power-assist by two or more humans is not found though this is very necessary in industries and households. Initiatives on cooperative manipulation of objects with power-assist by two humans have been taken (e.g.,[24]), however, the works are neither complete nor exclusive for cooperative manipulation. Hence, it is necessary to have an exclusive and complete model of power assist system for cooperative manipulation.
(lifting) of an object by two humans considering weight perception, load forces, motion etc. to make it human-friendly. However, such model has not been proposed yet.

Objective of this paper was to model a power assist system for cooperative lifting of objects with it by two humans, and to design and implement a weight-perception-based novel control strategy to improve its performances. The findings may be used to develop power assist robots for manipulating heavy objects in industries that may augment human’s abilities and skills and may improve interactions between robots and users.

II. EXPERIMENT SYSTEM DESIGN

We developed a 1-DOF (vertical up-down motion) power assist system using a ball screw actuated by an AC servomotor. Servomotor and ball screw were coaxially fixed on a metal plate and the plate was vertically attached to a wall (Fig.1(a)). We made three rectangular boxes by bending aluminum sheets (0.5mm thick). The boxes were lifted with robot and they were called power-assisted objects (PAOs). The dimensions (length x width x height) of the boxes were 6 x 5 x 16cm, 6 x 5 x 12cm and 6 x 5 x 8.6cm for the large, medium and small size respectively. Top of each box was covered with a cap made of aluminum sheet (0.5mm thick). The bottom and back were open. Self-weight of each box was about 13g on average. A force sensor (foil strain gauge type) was tied to the ball nut of the ball screw. An object (box), at a time, could be tied to the force sensor through an object holder and be lifted by a human (Fig.1 (b)).

We also made three ‘manually lifted objects’ (boxes) (MLOs) of different sizes (small, medium, large)(Fig.1 (c), (d)). MLOs were lifted manually and were not physically connected to the assist system. Shape, dimensions, material and outlook of a MLO of a particular size were same as that of the PAO of that particular size. It was possible to change the weight of the MLO by attaching extra mass to its back while keeping its front view unchanged. The MLOs were used as reference weights for estimating the perceived weights of the PAOs called power-assisted weights (PAWs).

The experimental power assist system is shown in Fig.2. Figure 3 shows the final arrangement for the experiments for cooperative lifting of objects with it. The PAO tied to the force sensor is to place on the soft surface of a table before it is lifted. Two handles are perpendicularly attached to the left and right sides of the PAO. Two subjects can grip two handles with their dominant hands using power grips and synchronously lift the PAO. The MLO is to place beside the PAO so that the MLO and outlook of a MLO of a particular size were same as that of the PAO of that particular size. It was possible to change the weight of the MLO while keeping the front view unchanged. The MLOs were used as reference weights for estimating the perceived weights of the PAOs called power-assisted weights (PAWs).

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III. DYNAMICS BASED ON WEIGHT PERCEPTION

According to Fig.3, the targeted equation of motion for lifting a PAO is (1).

\[ m \ddot{x}_d + mg = f_h. \]  

\[ (1) \]

Where,

\[ f_h = \text{Resultant load force applied by two humans} \]

As an attempt to introduce weight perception in the dynamic modeling, we hypothesized (1) as (2), where \( m_1 \neq m_2 \neq m \), \( m_1 \ll m, m_2 \ll m \), and hence \( m_1 \ddot{x}_d \neq m_2 \dot{g} \). Both \( m_1 \) and \( m_2 \) stand for mass. \( m_1 \) forms inertial force and \( m_2 \) forms gravitational force. A difference between \( m_1 \) and \( m_2 \) is considered due to the difference between perception and reality regarding the weight of the object lifted with the power assist robot. We then derived (3) ~ (5) based on (2).

\[ m_1 \ddot{x}_d + m_2 \dot{g} = f_h. \]  

\[ (2) \]

\[ \dot{x}_d = \frac{1}{m_1} (f_h - m_2 \dot{g}). \]  

\[ (3) \]

\[ x_d = \int \dot{x}_d \, dt. \]  

\[ (4) \]

\[ \dot{x}_c = \dot{x}_d + G(x_d - x). \]  

\[ (6) \]
IV. CONTROL DESIGN

We diagrammed the control based on (3)~(5) (Fig.4). If the system is simulated using Matlab/Simulink in the velocity control mode of the servomotor, the command velocity ($\dot{x}_c$) to the servomotor is obtained by (6), which is fed to the servomotor through a D/A converter. The controller is assumed to be common to two hands of two subjects because each trial is targeted to be in-phase, symmetric and synchronized. The resultant of the load forces of two hands and their cross-talks are to represent a common command. However, it is possible to design separate, but interacting controllers for each hand of each subject [20].

V. EXPERIMENT 1: DETERMINING RELATIONSHIPS BETWEEN ACTUAL AND PERCEIVED WEIGHS, EXCESS LOAD FORCE DETERMINATION, AND MOTION ANALYSES

A. Subjects

Ten mechanical engineering male students aged between 22 and 31 years (Mean=23.40 years, S.D. =2.6077) were selected as the subjects to voluntarily participate in the experiment. The subjects were right-handed, physically and mentally healthy.

B. Design of the Experiment

The independent variables were $m_1$ and $m_2$, and visual object size. The dependent variables were perceived weights (PAWs), peak load forces (PLFs), and object motions.

C. Experiment Procedures

The system in Fig.4 was simulated using Matlab/Simulink (solver: ode4, Runge-Kutta; type: fixed-step; fundamental sample time: 0.001s) for twelve $m_1$ and $m_2$ sets separately (Table 1). The experimenter randomly chose $m_1$ and $m_2$ set (e.g., $m_1 = 1.5, m_2 = 1$) and strictly maintained its confidentiality. For each $m_1$ and $m_2$ set, two subjects gripped two handles with their right hands using power grips and then synchronously lifted the PAO with the robot following a demonstration of the experimenter, maintained the lift for 1-2 seconds at a height of approximately 0.1 meter and then released the object. Then, each subject independently lifted a MLO using unimanual right handed power grip several times for reference weights. The MLO weight was sequentially changed in a descending order starting from 1.5 kg and ending at 0.1 kg maintaining a difference of 0.025kg (i.e.,1.5, 1.475,...0.125, 0.1kg). Thus, the subjects compared the perceived weight of the PAO (PAW) to that of the MLO (reference weights) and estimated the magnitude of the PAW. The performances were expressed through several criteria such as motion, object mobility, naturalness, stability, safety, ease of use etc., and in each trial the subjects subjectively evaluated (scored) the system using a 7-point bipolar and equal-interval scale as the following:

1. Best (score: +3)
2. Better (score: +2)
3. Good (score: +1)
4. Alike (score: 0)
5. Bad (score: -1)
6. Worse (score: -2)
7. Worst (score: -3)

All subjects conducted this experiment for small, medium and large objects separately. We recorded load force, motion (displacement, acceleration) and evaluation data for each trial separately. Figure 3 shows the experimental procedures.

VI. RESULTS OF EXPERIMENT 1

A. Psychophysical Relationship between Actual and Power-Assisted Weights (PAWs)

We calculated mean PAW for each $m_1$ and $m_2$ set for the small, medium and large object separately. Then, we drew graph for each size object separately taking the simulated gravitational mass ($m_2$) of twelve $m_1$ and $m_2$ sets as the abscissa and the mean PAWs for twelve $m_1$ and $m_2$ sets as the ordinate. Here, $m_3$ value was assumed as the actual weight of the PAO. Relationship between the actual weights and the PAWs for the large size object is shown in Fig.5.

Figure 5 shows that PAW is 0.125 and 0.25 kg for all $m_1$ values when actual weight is 0.5 and 1.0 kg respectively. We thus estimated that PAW was 25% of actual weight.
The figure shows that humans do not feel the change in \(m_1\) i.e., \(m_1\) do not affect PAWs. Analyses of Variances, ANOVAs (visual object size, subject) on PAWs for each \(m_1\) and \(m_2\) set showed that variations due to object sizes were not significant \((F_{2,18}<1\) for each \(m_1\) and \(m_2\) set). The reason may be that subjects estimated PAWs using haptic cues where visual cues of objects had no influences\[25]. Variations among subjects were also found statistically insignificant \((F_{9,18}<1\) for each \(m_1\) and \(m_2\) set).

### B. Analyses on Object’s Motions

Figure 6 shows time trajectories of object’s displacement and acceleration, and load force for a typical trial. We then derived the velocity for each trial based on the displacement time trajectory of Fig. 6 following (7) and determined their means for each object size separately.

\[
\text{Velocity (m/s)} = \frac{\text{MPD} - \text{MID}}{\text{TPD} - \text{TID}} \tag{7}
\]

In (7), MPD stands for magnitude of peak displacement, MID stands for magnitude of initial displacement, TPD stands for time corresponding to peak displacement and TID stands for time corresponding to initial displacement. We also derived the magnitude of peak acceleration for each trial based on the acceleration time trajectory and determined their means for each object size separately. Mean velocity and mean peak acceleration for different sizes of objects are shown in Table 2.

Results show that velocity and peak acceleration are proportional to object sizes \([25]\). Results also show that the accelerations are very large.

### C. Analyses on Load Forces and Excess in Load Forces

Based on the time trajectory of load force in Fig. 6, we derived the magnitude of peak load force (PLF) for each trial and determined the mean PLFs for each \(m_1\) and \(m_2\) set for each object size separately as shown in Table 3. We then plotted graph taking the \(m_1\) values of the twelve \(m_1\) and \(m_2\) sets as abscissa and the mean PLFs for the twelve \(m_1\) and \(m_2\) sets for the three objects as ordinate and determined the relationships between \(m_1\) and PLFs as shown in Fig. 7. The figure shows linear (approximately) relationships between inertia mass \((m_1)\) and PLFs.

We see in Table 3 that the lowest load forces were applied for the smallest values of \(m_1\) and \(m_2\) i.e., for \(m_1=0.5\), \(m_2=0.5\). We assumed that \(m_1=0.5\) kg, \(m_2=0.5\) kg might be the best amongst all twelve sets of \(m_1\) and \(m_2\) \([26]\). On the other hand, the actually required PLF to lift a PAO should be slightly larger than the PAW at \(m_1=0.5\), \(m_2=0.5\) \([25]\), which is 0.125 kg or 1.22625 N (Fig. 5). We compared the PAWs (Fig. 5) to the PLFs (Table 3) for the large, medium and small objects for \(m_1=0.5\), \(m_2=0.5\) and determined the excess in PLFs following (8) (Fig. 8). Results show that, on average, operators applied 8.003 times larger than the actually required PLFs. We also see that magnitudes of PLFs as well as the excess in PLFs are proportional to object sizes \([25]\).

We determined the mean evaluation scores for each size PAO for \(m_1=0.5\), \(m_2=0.5\). The detailed results will be presented later. The results showed that the system performances were not so satisfactory. We assume that the excessive PLFs produced excessive accelerations that in turn resulted in less satisfactory performances.

### Table 2: Mean Velocity and Peak Acceleration with Standard Deviations (in parentheses) for Lifting Different Sizes of Objects

<table>
<thead>
<tr>
<th>Object size</th>
<th>Velocity (m/s)</th>
<th>Peak Acceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.0539 (0.0016)</td>
<td>0.878 (0.05)</td>
</tr>
<tr>
<td>Medium</td>
<td>0.0621 (0.0052)</td>
<td>1.580 (0.09)</td>
</tr>
<tr>
<td>Large</td>
<td>0.0834 (0.011)</td>
<td>2.976 (0.1067)</td>
</tr>
</tbody>
</table>

### Table 3: Mean Peak Load Forces for Different Conditions

<table>
<thead>
<tr>
<th>(m_1, m_2) sets</th>
<th>Large (N) with standard deviations (in parentheses) for different object sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large</td>
</tr>
<tr>
<td>1</td>
<td>15.93 (1.231)</td>
</tr>
<tr>
<td>2</td>
<td>18.34 (1.76)</td>
</tr>
<tr>
<td>0.5, 0.5</td>
<td>11.57 (1.06)</td>
</tr>
<tr>
<td>1, 1.5</td>
<td>12.74 (0.62)</td>
</tr>
<tr>
<td>1.5, 0.5</td>
<td>13.99 (0.39)</td>
</tr>
<tr>
<td>2, 2.5</td>
<td>20.31 (1.19)</td>
</tr>
<tr>
<td>0.5, 0.5</td>
<td>14.47 (1.68)</td>
</tr>
<tr>
<td>1, 1.5</td>
<td>19.52 (1.01)</td>
</tr>
<tr>
<td>0.5, 1.5</td>
<td>16.89 (1.55)</td>
</tr>
<tr>
<td>1, 1.5</td>
<td>18.44 (1.74)</td>
</tr>
<tr>
<td>1, 1.5</td>
<td>17.23 (1.10)</td>
</tr>
<tr>
<td>2, 0.5</td>
<td>15.09 (1.19)</td>
</tr>
</tbody>
</table>
VII. EXPERIMENT 2: NOVEL CONTROL TO IMPROVE THE SYSTEM PERFORMANCES

Experiment 2 was conducted to reduce the excessive load forces by applying a novel control technique. The novel control was such that the value of $m_1$ exponentially declined from a large value to 0.5 when the subjects lifted the PAO with the robot and the command velocity of (6) exceeded a threshold (Fig.9). Reduction in $m_1$ would reduce PLF proportionally (Fig.7), and it would not adversely affect the relationships in (2) (Fig.5). We used (9) and (10) to modify the control of Fig.4. The digit 6 in (9) was determined by trial and error because the applied PLFs were at least 6 times larger than the actually required PLFs (Fig.8). Procedures for experiment 2 were same as that employed for experiment 1, but the system in Fig.4 was simulated using (9) and (10).

\[
m_1=6 \cdot e^{-6t} + 0.5 \] (9)
\[
m_2=0.5 \] (10)

VIII. RESULTS OF EXPERIMENT 2

We determined mean PLF for each size PAO for the modified control of experiment 2 (after control modification) and compared them to that determined in experiment 1 for lifting objects at $m_1=0.5$ and $m_2=0.5$ (before control modification). The results are shown in Table 4. Results show that the novel control strategy reduced PLFs significantly.

Mean peak accelerations for different object sizes after the control modification are shown in Table 5. The results show if we compare these to that before the control modification that peak accelerations significantly reduced. The reason may be that the reduced PLFs after control modification reduced the accelerations. On the other hand, velocity also slightly reduced due to control modification. However, reduction in velocity was very small and it did not affect performances.

Comparison of evaluation scores between experiments 1 and 2 are shown in Table 6 for the medium size object. The results show that the novel control improved performances through reducing excessive PLFs and accelerations, and the resulted performances are satisfactory.

Subjects felt reduced gravity for cooperative lifting because the gravity was shared by two subjects [21]. Synchronization between two subjects in cooperative lifting might be slightly less perfect, which might reduce the performances slightly [20].

ANOVARs showed that evaluation scores were not affected by object sizes. The reason may be that the subjects evaluated

We determined mean PAWs for each size object separately after the control modification and compared them to that derived in experiment 1 for $m_1=0.5$ and $m_2=0.5$ (Fig.10). The figure shows that mean PAWs were unchanged even though $m_1$ reduced exponentially due to control modification. It indicates that the control modification did not adversely affect the relationships of (2).

\[
\begin{align*}
\text{Start} & \quad m_1=6.5 \\
& \quad \dot{x}_c=> 0.005 \text{ m/s} \\
\text{Yes} & \quad m_1=6 \cdot e^{-6t} + 0.5 \\
\text{End} & \quad \text{Before modification} \\
\end{align*} \] Fig.9 The flowchart for the novel control strategy.

Table 4: Mean PLFs with standard deviations (in parentheses) for different object sizes before (experiment 1) and after (experiment 2) control modification

<table>
<thead>
<tr>
<th>Object size</th>
<th>Before modification</th>
<th>Mean PLFs (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>11.57(1.06)</td>
<td>10.18(1.14)</td>
</tr>
<tr>
<td>Medium</td>
<td>5.92(1.02)</td>
<td>5.247(0.095)</td>
</tr>
<tr>
<td>Small</td>
<td>6.113(0.14)</td>
<td>5.928(0.209)</td>
</tr>
</tbody>
</table>

Table 5: Mean peak accelerations with standard deviations (in parentheses) for different object sizes after control modification

<table>
<thead>
<tr>
<th>Object size</th>
<th>Mean peak acceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>1.06(0.1010)</td>
</tr>
<tr>
<td>Medium</td>
<td>0.762(0.232)</td>
</tr>
<tr>
<td>Small</td>
<td>0.453(0.157)</td>
</tr>
</tbody>
</table>

Fig.7 Linear relationships between inertial mass ($m_1$) and PLFs for different values of $m_2$ for different object sizes.

Fig.8 Excess in the peak load forces for different sizes of objects.

Fig.10 Mean PAWs with standard deviations for large, medium and small size objects for (a) $m_1=0.5$, $m_2=0.5$ (before control modification) and (b) $m_1=6 \cdot e^{-6t} + 0.5$, $m_2=0.5$ (after control modification).
performances using haptic cues where visual cues had no influences. Variations among subjects were also found statistically insignificant ($F_{5,18} < 1$ for each case). We also conducted ANOVAs (object size, subject) on peak load force, peak velocity and peak acceleration for experiments 1 and 2 separately. We found that variations between object sizes were significant ($p<0.01$ at each case). On the other hand, variations between subjects were not significant at each case ($p>0.05$ at each case).

**Table 6: Mean performances evaluation scores with standard deviations (in parentheses) for the medium size object before (Expt.1) and after (Expt.2) control modification**

<table>
<thead>
<tr>
<th>Evaluation criteria</th>
<th>Expt.1</th>
<th>Expt.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion</td>
<td>0.6667 (0.0774)</td>
<td>2.1667 (0.1754)</td>
</tr>
<tr>
<td>Mobility</td>
<td>1.1211 (0.0913)</td>
<td>2.1667 (0.1754)</td>
</tr>
<tr>
<td>Stability</td>
<td>1.0 (0)</td>
<td>2.0 (0)</td>
</tr>
<tr>
<td>Safety</td>
<td>1.0 (0)</td>
<td>2.0 (0)</td>
</tr>
<tr>
<td>Naturalness</td>
<td>0.7739 (0.1012)</td>
<td>1.9649 (0.1551)</td>
</tr>
<tr>
<td>Ease of use</td>
<td>0.8667 (0.0836)</td>
<td>1.9649 (0.1551)</td>
</tr>
</tbody>
</table>

IX. DISCUSSION

We assume that the resultant load force ($f_0$) derived in (2) can be further expressed as (11), where $f_{h1}$ and $f_{h2}$ are the load force for subject 1 and subject 2 respectively. We assume that $f_{h1} = f_{h2}$ and they are also synchronized. If $f_{h1} = f_{h2}$ is high and $f_{h1}$ and $f_{h2}$ are not so synchronized, the system may result in instability and lack of safety.

$$f_{h1} + f_{h2} = f_0 \quad (11)$$

X. CONCLUSIONS AND FUTURE WORKS

This paper successfully presents a model of power assist system and the design of its control for lifting objects with it by two humans cooperatively based on weight perception, load forces and motion features. We developed a model of power assist robot for lifting objects with it by two humans cooperatively. We included weight perception in dynamics and control. We determined psychophysical relationship between actual weights and PAWS, excess in load forces, and analyzed force and motion features. We then designed, implemented and evaluated a novel control based on human characteristics that improved the performances. The findings will help develop power assist devices that can satisfy most of the required conditions in manipulating heavy objects in industries. We will verify the results using heavy objects and real robots. Experiments in torque control mode of servomotor will be conducted to verify the results. The system will be upgraded to a real multi-DOF system.

REFERENCES


