Payload capacity of balanced robotic manipulators

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SUMMARY
The payload capacity of a conventional robot is usually limited as compared to the mass of the robot body. This is because a payload adds additional gravity loadings to the robot joints resulting in large input joint torques. To reduce the required input joint torques, the authors have proposed a mechanical balancing mechanism. Basically, the mechanism was designed to exactly balance the first three links of an articulated robot by adjusting the positions of counter-balancing masses so as to eliminate the gravity loading terms. Since the input joint torques are greatly reduced by adopting balancing mechanisms, a balanced robot is expected to carry heavier payload and move with higher speed and acceleration. This paper further investigates the possibilities of improving the payload capacity as well as speed and acceleration capabilities. These features were investigated under various operating conditions involving payload, maximum angular velocity, and acceleration period. Based upon the simulation results, the performances of the balanced robot are compared in detail with those of a unbalanced conventional robot.

KEY WORDS: Balanced robots; Payloads; Joint torques; Simulation.

1. INTRODUCTION
In recent years, industrial robots are being more extensively used in manufacturing automation. As the tasks are diversified, the robots are required to have more flexibility and a more uniform performance over a wide range of operating conditions. Also, it is necessary for the robots to move more rapidly for high productivity. Thus the robot has to work under heavy payload, high speed and acceleration conditions without losing accuracy and repeatability. Such capabilities have been considered as the ultimate goals of robot design and control, which are characterized by the dynamic characteristics of the robot, load, sizes of joint actuators and operating conditions.

A payload causes additional gravity loadings on the robot joints in addition to existing gravity loadings resulting from the weight of the links. Therefore, a heavy payload introduces large gravity loading torques. As operating speed increases, the coupling effects between joints are magnified resulting in large centrifugal and Coriolis torques. Also, when the robot moves at a high acceleration, large inertia torques are induced. Because of these phenomena, if high payload capacity and dynamic responsiveness (speed and acceleration capabilities) of a robot are required, large size joint actuators are required.

To reduce the required input joint torques, some efforts have been made utilizing the concepts of an arm balancing mechanism. These include a relief mechanism to minimize static loadings, a counter-balance device for the 4-bar linkage robot, an active gravity compensation method, and mass and spring balancing mechanisms. Chung et al. have studied the dynamic characteristics and control of balanced robotic manipulators. They designed mechanical balancing mechanisms implemented on a PUMA-760 robot. The balancing mechanisms were designed basically to compensate for the gravity loadings of the first three links of a PUMA-760 robot. This was accomplished by placing additional masses on the links of the robot so that the centers of masses of each link are located exactly at the joints. Their experimental and simulation studies showed that by the application of the balancing mechanism: (1) The inertia matrix becomes time-invariant for the joints 2 and 3; (2) Most of the velocity related terms are reduced to zero; (3) The gravity loadings are eliminated, thus significantly reducing driving joint torques; (4) Computation time required to generate the appropriate control inputs is drastically reduced. Also, they proposed a new concept of an "automatic balancing mechanism" (ABM) for articulated robots, which can actively balance each link according to the payload variation by moving the balancing masses. The detailed description of this mechanism can be found in references.

Since the driving joint torques are drastically reduced by employing the balancing mechanism, the size of joint actuators can be greatly reduced. In other words, the balanced robots can carry heavier payloads and work under higher speeds and acceleration conditions than the conventional robot. This paper investigates the possibilities of improving the payload capacity as well as the speed and acceleration capabilities of an articulated robot by introducing a balancing mechanism. The robot

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model used for this study is a PUMA-760 robot, and the
dynamic parameters are experimentally estimated.\textsuperscript{11} Based upon the derived dynamic equations over wide
ranges of operating conditions, including various payload
masses, operating speeds and acceleration periods, the
input joint torques of the balanced PUMA robot are
computed and compared with those of the conventional
unbalanced robot. Based upon the simulation results, the
payload capacity as well as the dynamic responsiveness
of the balanced robot are discussed in detail.

2. DYNAMIC EQUATIONS OF A BALANCED
ROBOT MOTION
We will consider a 3-degrees of freedom balanced
PUMA robot which is an articulated type manipulator,
as shown in Figure 1. In this figure, the links 2 and 3 are
shown to be equipped with balancing mechanisms. These
mechanisms are mechanical balancing devices which can
appropriately position counter-balancing weights to
eliminate gravity loadings acting on the joints 2 and 3,
including the weight of the payload. They are composed of
two parts, balancing mass fixtures and balancing
masses. The balancing mass fixtures are designed to
balance the robot with no payload condition when the
balancing masses are located in their initial locations.
When the manipulator picks up a payload, the balancing
mass of each axis moves from its initial position to an
appropriate position to balance the corresponding link.
Depending upon the payload magnitude the distance
varies for each balancing mass to travel.

To evaluate the payload capacity of a balanced
manipulator, we derive the dynamic equations of the
balanced robot and investigate the joint torque
characteristics of the manipulator. The dynamic equations
of motion of an articulated robot for the first three
joints can be written as:

\[
\sum_{k=1}^{3} D_{ik} \dot{\theta}_k + \sum_{m=1}^{3} H_{im} \ddot{\theta}_m + J_{im} \dot{\theta}_i + B_{im} \dot{\theta}_i + G_i = T_i - F_{ci} \quad (i = 1, 2, 3)\]  

The derivation of the equations (1) is based upon the
Lagrangian formulation. The derivation of these
equations can be found in references 9 and 10. Here, \( D_{ik} \)
is the 3 \times 3 acceleration related inertia matrix, \( H_{im} \)
is the non-linear Coriolis and centrifugal 3 \times 3 matrix for each
joint, \( G_i \) is the vector of gravity loadings for the \( i \)th joint,
\( T_i \) is the generalized torque, \( F_{ci} \) is the Coulomb friction
torque, \( B_{im} \) is the viscous friction coefficient associated
with joint \( i \), and \( \theta_i, \dot{\theta}_i, \ddot{\theta}_i \) are the angle, angular velocity,
and angular acceleration of the \( i \)th joint, respectively.

Also, \( J_{im} \) denotes the equivalent moment of inertia of the
\( i \)th joint motor related to each joint.

The dynamic equations of motion of the balanced
robot can be derived from equation (1) together with the
balancing conditions. the values of the inertial
parameters, \( J_{im} \) are changed from their original values by
the addition of the balancing mechanisms, as follows:

\[
\begin{align*}
J_{i11}^{\cdot} &= J_{i11} + \frac{1}{2} \{ -I_{iex}^{\cdot} + I_{iy}^{\cdot} + I_{iz}^{\cdot} \} + m_i^{\cdot}(\dot{x}_i^{\cdot})^2 \\
J_{i22}^{\cdot} &= J_{i22} + \frac{1}{2} \{ I_{iex}^{\cdot} + I_{iy}^{\cdot} + I_{iz}^{\cdot} \} + m_i^{\cdot}(\dot{y}_i^{\cdot})^2 \\
J_{i33}^{\cdot} &= J_{i33} + \frac{1}{2} \{ I_{iex}^{\cdot} + I_{iy}^{\cdot} - I_{iex}^{\cdot} \} + m_i^{\cdot}(\dot{z}_i^{\cdot})^2 \\
J_{i12}^{\cdot} &= J_{i12} + m_i^{\cdot}\dot{x}_i^{\cdot}\dot{y}_i^{\cdot} \\
J_{i13}^{\cdot} &= J_{i13} + m_i^{\cdot}\dot{x}_i^{\cdot}\dot{z}_i^{\cdot} \\
J_{i23}^{\cdot} &= J_{i23} + m_i^{\cdot}\dot{y}_i^{\cdot}\dot{z}_i^{\cdot} \\
J_{i14}^{\cdot} &= J_{i14} + m_i^{\cdot}\dot{x}_i^{\cdot}\dot{z}_i^{\cdot} \\
J_{i24}^{\cdot} &= J_{i24} + m_i^{\cdot}\dot{y}_i^{\cdot}\dot{z}_i^{\cdot} \\
J_{i34}^{\cdot} &= J_{i34} + m_i^{\cdot}\dot{z}_i^{\cdot}\dot{z}_i^{\cdot} \\
J_{i44}^{\cdot} &= m_i^{\cdot} + m^{\cdot} \quad (i = 2, 3) .
\end{align*}
\]

Here, the superscript “b” denotes the balanced sytem.
The \( I_{iex}^{\cdot}, I_{iy}^{\cdot}, \) and \( I_{iex}^{\cdot} \) represent the moments of inertia of
the balancing mechanism with respect to the mass center
of mechanism, \( m_i \) and \( m_i^{\cdot} \) are the mass of the \( i \)th link and
the mass of the corresponding balancing mechanism
respectively, and \( \dot{x}_i^{\cdot}, \dot{y}_i^{\cdot}, \) and \( \dot{z}_i^{\cdot} \) denote the locations of
the center of mass of the balancing mechanism in the \( i \)th
link coordinate frame. From equation (2) and the gravity
loading torques, such as \( G_2(\theta) \) and \( G_3(\theta) \), balancing
conditions can be derived. By locating the balancing
masses according to a payload, the gravity loading
torques of the balanced robot are reduced to zero. The
values of \( \dot{x}_i^{\cdot} \) and \( \dot{z}_i^{\cdot} \) to accomplish exact balancing at each
joint can be calculated as follows:

\[
\begin{align*}
\dot{x}_i^{\cdot} &= \frac{-J_{i14} + (m_2 + m_3 + m_5)\alpha_2}{m_2 - \alpha_2} \\
\dot{z}_i^{\cdot} &= -J_{i34}/m_4 .
\end{align*}
\]

When a robot is balanced by placing the balancing
mechanisms in their corresponding locations as indicated
in the above equations, the following equations hold for
a given payload:

\[
\begin{align*}
J_{i14}^{\cdot} + (J_{i24}^{\cdot} + J_{i34}^{\cdot})\alpha_2 &= 0 \\
J_{i34}^{\cdot} &= 0 .
\end{align*}
\]

Using equations (1)–(4), the dynamic equations of
motion of the balanced robot can be derived, and its

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Fig. 1. Schematic diagram of the balanced PUMA-760 robot.
dynamic coefficients are given by \(^{9,10,12}\)

\[
D^b_i = J_{i1} + J_{i11} + J_{i33} + J_{i32} + (J^b_{i4} + J^b_{i4a})d^b_2 \\
+ (J^b_{i11} + J^b_{i1a}d_2)C_2 + J^b_{i22}S_2 + J^b_{i11}C_2 + J^b_{i33}S_2
\]

where \(S_2 = \sin \theta_2, C_2 = \cos \theta_2, S_{22} = \sin (\theta_2 + \theta_3), C_{22} = \cos (\theta_2 + \theta_3), g \) is the gravitational constant, and \(d_2, d_3 \) denote the length of the 2nd link and the offset between first and the 2nd link, respectively. By introducing the balancing mechanisms, the dynamic properties of the balanced robot described in equation (5) have many distinct and favorable features when compared to those of the conventional unbalanced robot.\(^{9,10}\) (1) The inertia torque terms related to the links 2 and 3 are independent of the configuration of the robot, and those of the link 1 are greatly simplified; (2) Most of the centrifugal and Coriolis torque terms are reduced to zero or drastically simplified; (3) Gravity loading torques are reduced to zero. However, it should be noted that the simple dynamic characteristics of the balanced robot derived here were obtained on the assumption that the balancing conditions given in equation (4) exactly hold. In the next section, we will investigate the payload capacity of the balanced manipulator in relation to various operating conditions.

3. PAYLOAD CAPACITY OF THE BALANCED ROBOT

The payload capacity of a robotic manipulator can be considered as the maximum payload mass that a robot can lift in its fully extended configuration without overloading the actuator. This is the static payload capacity of the robot which is determined by the gravity loadings only. But when the robot executes a specified trajectory motion with this maximum payload, the required input torques may exceed the torque limits of the joint motors since the dynamic effects of links and load induce additional inertia and Coriolis torques. Thus, the payload capacity of a robot should be determined by considering the dynamic characteristics of the robot.\(^{13}\)

Suppose the input joint torques are bounded as:

\[
|T_i| \leq T_{L,i} \quad (i = 1, 2, 3)
\]

where the torque limit, \(T_{L,i} \) is a constant. The input joint torques, \(T_i \) are functions of the manipulator configuration and the inertial properties of the manipulator and payload as shown in equations (1) and (2). For a given path motion and a payload condition, the torque limits in equation (6) determine the payload capacity of the robot.

To evaluate the payload capacity, a series of simulation studies were performed based upon the dynamic modeling described in the previous section. The dynamic parameters of the balanced robot used in this study are presented in Table I. They were estimated experimentally, and verified to accurately represent the actual dynamics of the PUMA-760 robot motion.\(^{14}\) A detailed description of the identification experiment can be found in references\(^{11,14}\). Using these data, the required input torques were computed for a given trajectory motion using equations (1), (2), and (5). After the input joint torques had been calculated at each discrete point along the trajectory path, they were compared with the limiting torques using equation (6) to find whether any of the input joint torques was beyond the limiting torques. This procedure was repeated by varying the payload conditions, until one of the joint actuators was overloaded. In this way, the payload capacity of the robot was determined.

Since the dynamic characteristics of a robot depend upon the robot configuration, the work trajectory was chosen to cover a more general work space. The motion range for each joint was given as: from \(-90 \) to \(-4 \) degree for joint 1, from \(-20 \) to \(-106 \) degree for joint 2, and from \(10 \) to \(24 \) degree for joint 3, which indicates an
ascending motion of joints 2 and 3, as shown in Figure 2. The velocity profile was chosen to have a trapezoidal shape, as shown in Figure 3. The acceleration period was chosen to be 1.0 sec. The maximum angular velocities of the links were chosen as 1.0 rad/sec which is the maximum allowable angular speed of the PUMA-760 robot. The joint torque limit often depends upon the velocity due to input power limitation and thermal effect on motor performance. In this simulation study, the torque limits were determined on the assumption that the attainable region of angular speed and motor torque are restricted by the rated output power on the speed-torque characteristic curve. Since the joint motors have the same rated power of 770 W, the joint torque limit \( T_{L_i} \) was chosen to be 770 N.m. With these fixed limiting torques, the simulation studies were performed to investigate the payload capacities of the balanced robot under various operating conditions.

4. RESULTS AND DISCUSSIONS

Figure 4(a) shows the input joint torques of the conventional PUMA-760 robot which handles a 5 kg payload with the maximum angular speed of 1.0 rad/sec. Since the joint 1 inherently has no gravity loading, the required torque of joint 1 contains only inertia, velocity related terms and Coulomb friction terms, as shown in Figure 4(a). The inertia torque of this joint exactly follows the trapezoidal velocity profile, and the Coulomb friction torque is constant during the entire trajectory motion. The torque characteristics of joints 2 and 3 are different from those of joint 1, because there always exist large gravity loadings for all trajectory motions. The peak gravity loading is reached near at the beginning of the trajectory motion for both joints, since at this instant the robot is at its fully extended configuration. The gravity loading torque of joint 2 is much larger than that of joint 3. This is because the weight of link 3 itself, as well as the payload, contributes to the gravity burdens on joint 2 which is already under its own gravity loadings, whereas link 3 experiences gravity loadings of link 3 itself and the payload. Since the test motion is ascending for joints 2 and 3, which means that the signs of Coulomb friction and gravity loading are the same, these torque terms add up to increase the required input torques. The situation is reversed if we move the manipulator downward, and thus the two torque terms cancel each other out to reduce the total torque. As it can be seen from the figures, the inertia torque plays an important role in the dynamics of joint 1, while the gravity loadings are dominant for joints 2 and 3. This feature becomes more accentuated under heavier payload condition. As can be seen from the figures, the maximum joint torques during the trajectory motion were reached near at the beginning for all joints. The joint 2 suffers from the largest loading torque, and the torque value reaches near limiting torque. This implies that the payload capacity of the unbalanced PUMA robot is determined by the maximum loading torque of joint 2.

When we implement the balancing mechanism on the conventional PUMA-760 robot, the dynamic characteristics is changed as shown in Figure 4(b). Since the balanced robot has no gravity loading terms, as presented in equation (5), the required torques of all joints contain only inertia, velocity-related terms, and Coulomb friction terms. The torque behavior in the initial acceleration and final deceleration periods, which shows a nearly trapezoidal trajectory profile, is mainly
related to the inertia terms. During the constant angular velocity period, the driving torques of joints 2 and 3 are nearly constant because of absence of gravity loadings. In contrast to the case of the conventional robot, inertia torques dominate other torque terms. The maximum joint torque during the trajectory motion occurs at the end of the initial acceleration period for joints 2 and 3, while for joint 1 the maximum torque occurs at the beginning of this period. The inertia torques of the balanced manipulator are found to be slightly higher for all joints when compared with those of the unbalanced robot. This is due to the addition of the balancing masses to links 2 and 3. Because of this, the peak torque of joint 1 of the balanced robot is slightly increased by 51 N.m. However, the peak values of the required input torques of joints 2 and 3 are found to be drastically reduced by about 317 and 138 N.m, respectively. This is because rather large gravity loading torques are eliminated. The reduction of the peak torques will be even more pronounced for heavier payload conditions.

When each link is balanced, a heavier balancing mass will travel shorter distances from its initial location than a lighter balancing mass does for the same payload. Since the inertia torque induced by a balancing mass is proportional to its mass and square of its distance from the joint axis, the heavier balancing mass results in a smaller inertia torque than the lighter balancing mass does. Therefore, if a heavier balancing mass is used for a given payload, the peak value of the required input torque of each joint decreases. However, a heavier balancing mass $BM_2$ does not always reduce the maximum torques of joints 1 and 2 for a given payload, as we will see later. In Figure 5 the effect of balancing mass $BM_2$ on the maximum joint torques is shown for various payloads when $BM_2$ remains fixed at 120 kg. As the balancing mass $BM_2$ increases, the maximum torque of joint 3 decreases, while the maximum torques of joints 1 and 2 slightly increase with the weight of $BM_2$ greater than a certain value. Thus, it is not always advantageous to increase the balancing mass $BM_2$, and an optimal weight of $BM_2$ exists for a given payload. These results indicate that an optimal choice of the balancing mass $BM_2$ is necessary according to the payload.

Figure 6 shows the variations of the maximum input torques of the conventional unbalanced and balanced robots during the given trajectory motion under various payload conditions. The limiting torques are represented as horizontal lines in this figure. As shown in the figures, the maximum input torques are drastically reduced when the balancing mechanisms are employed, especially for joint 2. As payload increases, the maximum torque of joint 2 exceeds the limiting torque first, while those of joints 1 and 3 are far below the limiting value. Thus, the maximum joint torque of joint 2 determines the payload capacity of the PUMA robot: Based upon this criterion, the payload capacity of the conventional unbalanced robot is 7 kg, while that of the balanced robot is 67 kg.

This indicates that the payload capacity of the PUMA robot is improved by about 9 times by introducing the balancing mechanism.

Fig. 5. Maximum joint torques of the balanced robot during the trajectory motion; $t_a = 1.0$ sec, $V_{max} = 1.0$ rad/sec, $BM_2 = 120$ kg.

Fig. 6. Variation of the maximum joint torques with payload; $t_a = 1.0$ sec, $V_{max} = 1.0$ rad/sec, $BM_2 = 120$ kg, $BM_3 = 60$ kg.
In addition to handling capability of payload, the dynamic responsiveness (velocity and acceleration capabilities) of the balanced robot was also investigated. Figure 7 shows the variations of the maximum joint torques of the balanced robot for a given payload when the acceleration period was varied from 0.4 sec to 1.0 sec. In this study, the acceleration period, \( t_a \) indicates the time elapsed for the angular velocity to reach the maximum value as shown in Figure 3. As the acceleration period decreases, the angular acceleration of the links increases, since the maximum angular velocity is fixed. The results show that the maximum input joint torques increase with a decreasing acceleration period, and eventually the input torque of joint 2 exceeds the limiting torque. The payload capacities of the balanced robot can be shown for various acceleration periods in Table II. When the acceleration period is 1.0 sec, the allowable payload mass is 63 kg. On the other hand, when the acceleration period is 0.4 sec, the robot can move a payload of only 1 kg mass. When the payload is 7 kg which is the same as the payload capacity of the conventional unbalanced robot, the acceleration period can be increased from 1.0 sec to 0.43 sec by applying the balancing mechanism. In other words, the balanced PUMA robot can accelerate with 2.3 rad/sec\(^2\), while the conventional robot can accelerate only with 1.0 rad/sec\(^2\).

In Figure 8 the maximum joint torques of the balanced robot are depicted for various payload masses when the maximum angular velocities, \( V_{\text{max}} \), are varied from 1.0 rad/sec to 2.5 rad/sec. The accelerations in initial period are fixed at 1.0 rad/sec\(^2\). As expected, the joint 2 experiences maximum input torques for all the conditions, and the maximum torque of joint 2 reaches the limiting torque first. The payload capacity of the balanced robot is reduced from 66.8 kg to 10.8 kg, as \( V_{\text{max}} \) varies from 1.0 to 2.5 rad/sec, as shown in Table II, when the limiting torques were fixed at 770 N.m. For a 7 kg payload, the balanced robot can move with a maximum angular velocity of 2.65 rad/sec.

### TABLE II Maximum allowable payload for the given operating conditions

<table>
<thead>
<tr>
<th>( V_{\text{max}} ) = 1.0 rad/sec</th>
<th>( t_a ) = 1.0 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_a ) (sec)</td>
<td>( m_p ) (kg)</td>
</tr>
<tr>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>0.43</td>
<td>7.0</td>
</tr>
<tr>
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<td>30.5</td>
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<tr>
<td>0.8</td>
<td>50.9</td>
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<tr>
<td>1.0</td>
<td>66.8</td>
</tr>
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</table>

5. CONCLUDING REMARKS

The balancing mechanisms were applied to an articulated robot to investigate the effect of the mechanisms on payload capacity. Based upon the derived dynamic equations, the input joint torques of the balanced PUMA robot were computed and compared with those of the conventional unbalanced one. These simulation studies were performed for various operating conditions by varying the payload, acceleration period and maximum angular velocity.
The simulation result shows some apparent improvements on the dynamic performance of a robot by the use of the balancing mechanism. The most significant improvement is that a drastic reduction of the joint torque of joint 2 can be achieved. Such a feature is most advantageous under heavier payload conditions because this joint undergoes the largest required joint torques, thus limiting allowable payload of a robot. As a result, the payload capacity is drastically increased; in fact, it may handle an about 9 times heavier payload. In addition, the balancing mechanism improves the acceleration and velocity capabilities. The simulation result shows a reduction in the angular acceleration period by about a half, which implies that the balanced robot can be operated with twice as large angular acceleration. Also, the balanced robot can operate with an approximately 3 times higher velocity, as compared with a conventional robot. Hence the redesigned, balanced robot can handle much heavier payloads, and can be operated at a much higher speed.

References
