Mechanism and Control of a Dynamic Lifting Robot

T. Ueno[a], N. Sunaga[a], K. Brown[b] and H. Asada[b]

[a]Institute of Technology, Shimizu Corporation, Etchujima 3-4-17, Koto-ku, Tokyo 135, Japan
[b]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract

This paper focuses on a new approach to robot design and control for dealing with heavy loads. Referring to human dynamic motion, we studied dynamic task strategies to create large forces by dynamically moving the internal body. Much greater force can be obtained by this technique than the traditional quasi-static technique. Kinematic and dynamic behavior of human and robot is analyzed with dynamic lifting of a heavy weight. The dynamic trajectory of the internal body motion as well as one for the end effector motion are optimized by parametric representation of dynamic task performance. A prototype robot is designed, constructed and tested. Experiments demonstrate the feasibility and effectiveness of the dynamic task strategies.

1. Introduction

Industrial robots which was developed in 1960s' popularized in 1980s' and widely used in manufacturing industry such as automobile industry. Main feature of these industrial robots are able to repeat same action precisely. Therefore, research and development trends of these robots has been focused on high-precision and high speed.

On the other hand, the need for a robot in non-manufacturing industry such as construction, agriculture and forest industry are somewhat different from the need for a robot in manufacturing industry. Those are large rated load, mobility and light weight. A ratio of a rated load and weight of typical industry robot is less than 0.1. Which means that the industry robot can only handle a work less than ten percent of its weight. So that, typical industry robots are hardly available for non-manufacturing industry.

Human can handle a object more efficiently than a robot. For example, the top athlete of weight lifting can lift the weight of a barbell more than three times heavier than his weight. Human uses dynamic motion efficiently to lift a barbell.

Previous work of a dynamic robot can be found in some area. Dynamic body motions have been studied in the area of leg locomotion. Dynamic motion control of robot end effector has been studied in manipulation research. Force plate measurement was used to collect data for a variety of athletic activities to make qualitative comparisons between well trained and moderately trained athletes.

This paper describes a study of human dynamic motion, the design and construction of prototype robot, method of computing trajectories for the robot, and the results of the prototype robot tests for the dynamic task.

2. Human Dynamic Motion Analysis

Human dynamic motion was studied in order to understand how human perform dynamic task. We assumed a human model as a two dimensional string of n mass less links with the human's body mass located in the middle of the chain of links to explain forces production for these dynamic tasks. Considering this model, we measured the position trajectories of only the humans center of mass and end effector. We also measured the force produced through the end effector and the human feet.

2.1 Measurement of Athletes' Lifting Motion

Top athletes of Weight Lifting can lift as much as three and a half times their weight to a position over their head very quickly. They use so called "dynamic lifting technique" in which the whole body motion is precisely coordinated with the barbell motion.

Figure 1. shows experimental setup for measuring human lifting motion. Two video cameras were used to record the motion of the subject. The subject's motion was recorded from front with high speed video camera, and side motion was recorded using normal speed video camera. Markers were set on the joint and center of the subject's body as well as on the lifted mass.

Forces were measured by force plate on the floor and force sensor attached to the bar.

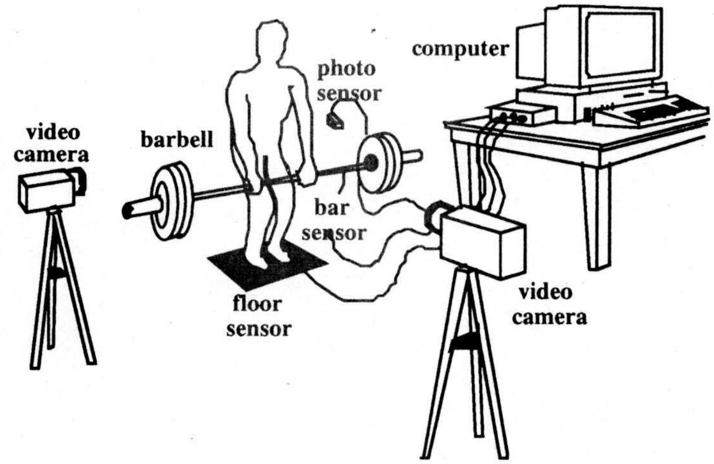

Figure 1. Experimental Setup

2.2 Experiment Result

Figure 2. shows the time profile of the vertical displacement of the bar and subject's approximate center of mass taken during a 205 lbs.(93kg) "power clean". The side view of the subject was digitized from the video image.

There is a small flat spot in the trajectory of the bar labeled stall point. Another feature is the peek of the subjects centroid as the bar continues to move upward.

Figure 3. shows the force profile during the same lifting. For comparison purposes, the forces on the floor has been inverted and subject's weight has been subtracted.

Main characteristic of this result is that the force to the floor showed large peek and dip in the final stage of power clean. This means that the subject utilized dynamic motion to pass the arm position which is hard to produce large power to the bar.

Another example of dynamic motion of the human is to measure dynamic force produced by human an experiment of opening a stuck door. Force sensor was set at the door handle and the floor to measure the force. We can not show the detail of this experiment here, but we made clear that the subject uses dynamic motion for this action, too.

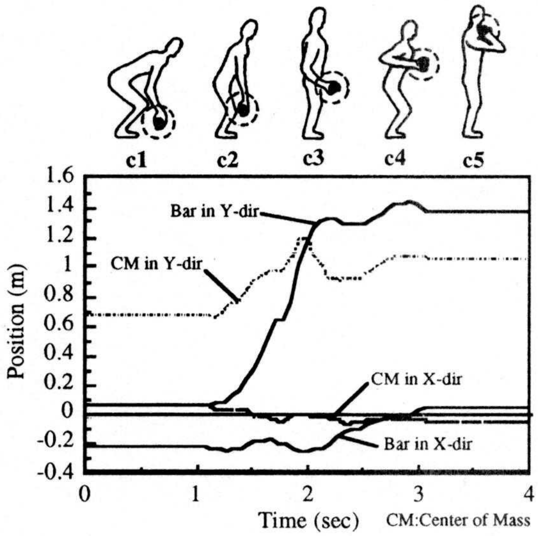

Figure 2. Vertical motion of the subject and bar

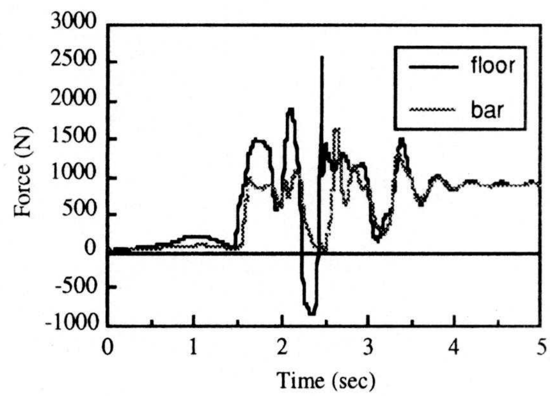

Figure 3. Force measured during lift

3. Kinematics of a Dynamic Robot

We designed dynamic robot to simulate human dynamic motion. We assumed a dynamic robot model as a two dimensional string of n mass less links with the robot's body mass located in the middle of the chain of links. Figure 4. shows the model of dynamic robot lifting a mass.

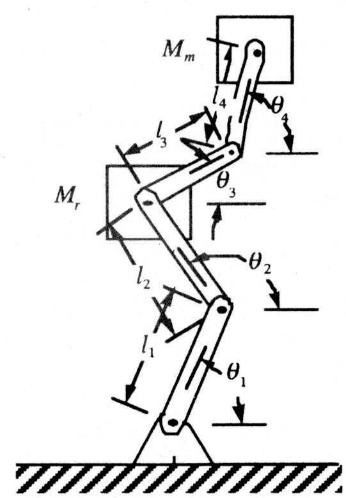

Figure 4. Model of Dynamic Robot Lifting a Mass

If we use this simplified model, we can compute the robot's equations of motion. By choose $\theta_1,\theta_2,\theta_3,\theta_4$ to be our generalized coordinates, we can write the equations of motion in terms of generalized torque.

These are the torque created at each of the joints by actuators that would be located in base.

$$Q_1 = H_{11}\ddot{\theta}_1 + H_{12}\ddot{\theta}_2 + H_{13}\ddot{\theta}_3 + H_{14}\ddot{\theta}_4 - h_{211}\dot{\theta}_2^2 - h_{311}\dot{\theta}_3^2 - h_{411}\dot{\theta}_4^2 + (M_r + M_m)gl_1\cos\theta_1 \tag{1}$$

$$Q_2 = H_{21}\ddot{\theta}_1 + H_{22}\ddot{\theta}_2 + H_{23}\ddot{\theta}_3 + H_{24}\ddot{\theta}_4 + h_{211}\dot{\theta}_1^2 - h_{322}\dot{\theta}_3^2 - h_{422}\dot{\theta}_4^2 + (M_r + M_m)gl_2\cos\theta_2 \tag{2}$$

$$Q_3 = H_{31}\ddot{\theta}_1 + H_{32}\ddot{\theta}_2 + H_{33}\ddot{\theta}_3 + H_{34}\ddot{\theta}_4 + h_{311}\dot{\theta}_1^2 + h_{322}\dot{\theta}_2^2 - h_{433}\dot{\theta}_4^2 + M_m gl_3\cos\theta_3 \tag{3}$$

$$Q_4 = H_{41}\ddot{\theta}_1 + H_{42}\ddot{\theta}_2 + H_{43}\ddot{\theta}_3 + H_{44}\ddot{\theta}_4 + h_{411}\dot{\theta}_1^2 + h_{422}\dot{\theta}_2^2 + h_{433}\dot{\theta}_3^2 + M_m gl_4\cos\theta_4 \tag{4}$$

where Q_1, Q_2, Q_3, Q_4 are the generalized torques. H_{ij} are the Inertial mass terms.

$$H_{ij} = (M_r + M_m)l_i l_j \cos(\theta_j - \theta_i) \qquad (i = 1\ to\ 4\ and\ j = 1\ to\ 2)$$

$$H_{ij} = M_m l_i l_j \cos(\theta_j - \theta_i) \qquad (i = 1\ to\ 4\ and\ j = 3\ to\ 4)$$

$$h_{211} = (M_r + M_m)l_1 l_2 \sin(\theta_2 - \theta_1)$$

$$h_{ijj} = M_m l_i l_j \sin(\theta_j - \theta_i) \qquad (i = 3\ to\ 4\ and\ j = 1\ to\ 3)$$

Since the actuators are located at M_r , and not at the base, we need to find the relationship between the actuator torques and the generalized coordinates. This relationship is;

$$\tau_1 = -Q_1 - Q_2 - Q_3 - Q_4, \tag{5}$$

$$\tau_2 = Q_1, \tag{6}$$

$$\tau_3 = Q_3, \tag{7}$$

$$\tau_4 = Q_4. \tag{8}$$

where τ_i is the torque of each motor.

4. Dynamic Task Trajectories

An optimal trajectory for the four degree-of-freedom dynamic robot to lift a heavy object will be generated based on the motion data acquired from weight lifting athletes. It should be noted that the trajectories of human athletes are not directly applicable to the robot, because the human and the robot are different in kinematic structure, mass distribution, and actuators.

We need to extract features essential to the dynamic lifting strategy, and apply them to the robot. The method for synthesizing an optimal trajectories can be described as follows:

1) Extract a motion pattern from human data, and parameterize the motion pattern.
2) Formulate an optimization problem by using robot's dynamic equations and performance index for evaluating the robot task.
3) Solve the optimization problem using a recursive optimization algorithm with initial values obtained from human lifting data.

Figure 5. shows the simplified trajectory patterns for the body and the barbell motion divided into n segments, and the parameters of dynamic lifting trajectories. The position trajectories of the body centroid and the weight, denoted Y(t) and y(t) are given by

$$Y(t) = \frac{1}{2}A_i(t - t_{i-1})^2 + V_{i-1}(t - t_{i-1}) + Y_{i-1} \tag{9}$$

$$y(t) = \frac{1}{2}a_i(t - t_{i-1})^2 + v_{i-1}(t - t_{i-1}) + y_{i-1} \tag{10}$$

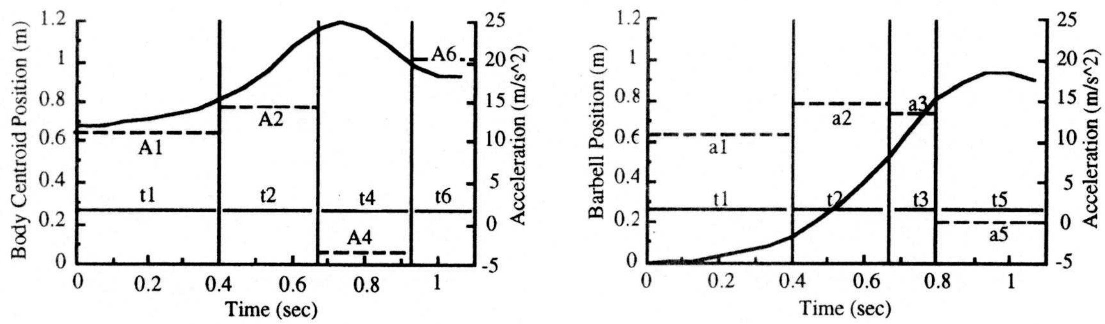

Figure 5. Trajectories derived from human motion barbell

Those parameters can be shown **q** as the parametric representation. **q** is the vector consisting of all the parametric representation of the trajectories.

$$\mathbf{q} = \left[A_1, \ldots, A_n, a_1, \ldots, a_n, t_1, \ldots, t_n\right]^T \tag{11}$$

From these parameterized trajectory, inverse kinematics can be computed using a kinematic model of the robot. Actuator torques τ_i necessary to move the end effector and center of mass through the motion trajectories can be computed using the equations of motions for the robot model. Figure 6. shows the optimization process of dynamic task trajectories.

For the evaluation of trajectory, we consider the performance index given by

$$PI = \underset{1 \le j \le n}{Max} \int_0^{t_f} \left(\tau_j(t)\right)^2 dt, \tag{12}$$

where $\tau_j(t)$ is the torque of the j-th actuator, n is the number of actuators and t_f is the final time of the motion. The performance of each motor is limited by the rise of temperature of the motor caused by the generation of large torque. Therefore, the trajectory optimization problem can be stated as to reduce temperature rise of the weakest motor. Which means that the evaluation is to balance the distribution of torques of each motor. Using a performance index PI, the motion and torques can be evaluated.

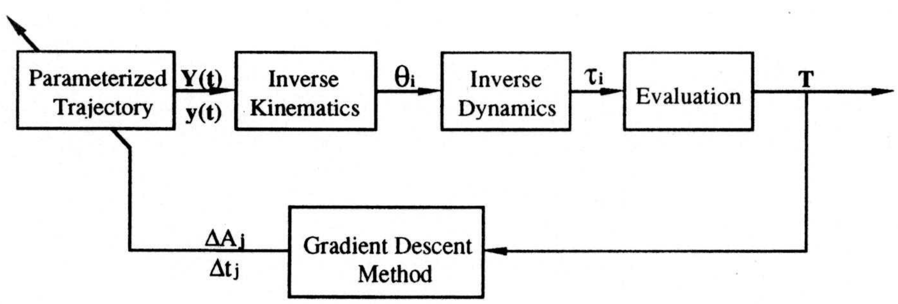

Figure 6. The optimization process

5. Design of Prototype Dynamic Robot

Two prototype dynamic robot is designed and developed. One is developed in MIT and the other is developed in Shimizu Corporation. Prototype robot which is developed in Shimizu is introduced in this chapter.

Figure 7. and Photo 1. shows the construction of the Dynamic Robot. Table 1. shows the specifications of the robot. The height of the robot is approximately 1.4 m. The length of each links of the robot are a little bit shorter than human's arms and legs. The length of its body is very short compare to human's body. To concentrate the mass to the center of the robot, four motors are set in the middle of the robot. Each arms are driven by these motors and timing belt.

Duralumin is used for Main structural material of the arm to reduce its weight. Four AC servo motors are used for actuator of the robot. Each motor is connected to reduction gear. Gear ratio of the reduction gear is different between the gear box for upper arm and lower arm. Personal computer (NEC PC-9821 Ap3: CPU DX4 100MHz) is used for the controller of the dynamic robot system.

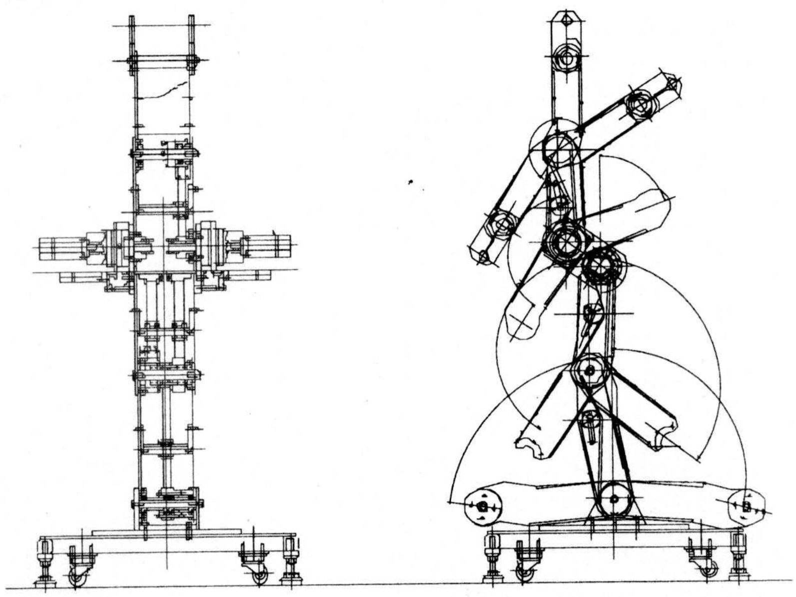

Figure 7. Front and Side View of the Dynamic Robot

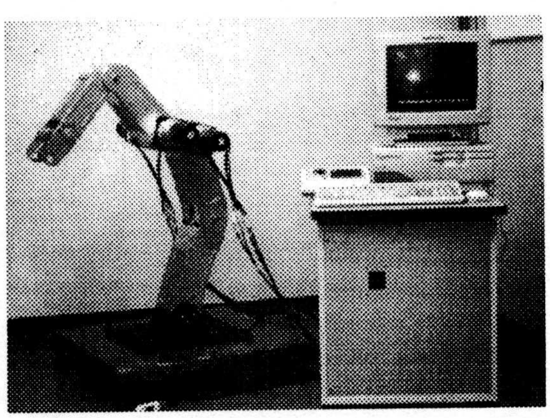

Photo 1. Dynamic Robot and Control System

Table 1. Specifications of the Dynamic Robot

Manipulator	Mechanical Structure	Articulated Robot
	Degrees of Freedom	4
	Max. Velocity (Arm 1, 2)	120 deg/sec
	Max. Velocity (Arm 3, 4)	640 deg/sec
	Actuator	AC servo motor
	Dimensions	1400 mm (Height)
	Weight	38 kg
	Power Supply	100 V AC
Control System	Control Computer	NEC PC9821 Ap3
	Motion Control Method	CP
	Programing Method	Off-Line Teach
	Power Supply	100 V AC

6. Experiment of Prototype Robot and the Results

6.1 Experimental Setup

The prototype robot was connected to the servo amplifiers and the amplifiers where connected to an D/A board located in the computer. The encoders of each motor were also connected to the computer through the counting board. The robot performs preprogrammed trajectory by using PD control. Control program was written in C language.

Lifting motion was selected for the dynamic motion experiment. And the weight is set the end of manipulator. Trajectory of the robot was obtained by the optimization method described in chapter 4. Figure 8. shows a simulated movement of the lifting experiment.

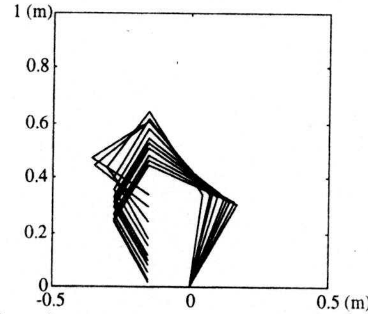

Figure 8. Simulated movement of the dynamic lift of the robot

6.2 Results

To show the benefits of the dynamic lifting technique, the comparison trajectory was synthesized to compare to the optimized trajectory. The comparison trajectory was designed with a constant acceleration for the lifted mass and another constant acceleration for the robots centroid.

Figure 9. shows the result of 20kg mass lifting trajectories of dynamic technique and comparison trajectories. In this experiment, trajectory optimization is done by reducing the torques of the motor for link 3 and 4 to simulate human lifting motion. Because the leg muscle of human is stronger than the arm muscle.

Figure 10. shows the integrated torque $\Sigma(\text{torque})^2$ of each motor during the experiment time(1sec). This data shows that integrated torque of motor 3 and 4 in case of dynamic is smaller than the data from the comparison trajectory. This result demonstrated the effectiveness of the dynamic technique.

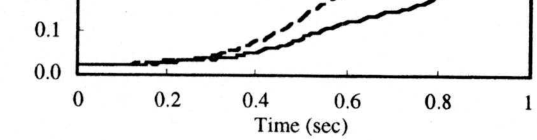

Figure 9. The optimal and comparison trajectory

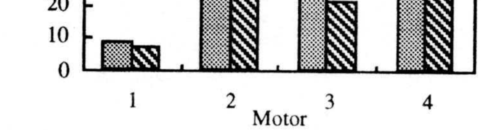

Figure 10. $\Sigma(\text{torque})^2$ for dynamic vs. comparison

7. Conclusion

Most of construction operation includes heavy material handling and assembly. Those tasks still rely on labor and crane. Industrial robots are used in manufacturing industry, but can hardly use in construction industry especially for heavy material handling in the building. Large crane and forklift can not use in the building under construction.

A new approach which use dynamic motion control is proposed. The strategy of the dynamic task performance is consists of three points. One is to store a large momentum in the inertial body motion and discharge the momentum at the interaction between the robot's end effector and the environment. Second, the take advantage of specific posture of the arm and leg to create a large mechanical advantage which allows for efficient load bearing and transmission of actuator torque to the end effector. Third, peak output of robot actuators are utilized for short period of time. These peak outputs can be much higher than their continuous rated outputs.

Dynamic task strategy is modeled and analyzed along with a heavy weight lifting. From the development and experiment of prototype robot, we made clear that the dynamic task strategies are feasible and effective.

A small and light weight heavy-duty handling robot will be feasible by using this dynamic task strategy. This technique is applicable not only for lifting but for puling, peeling and destroying work. Those operation is common in construction, this technique is expected to be widely used in construction industry.

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