Increasing Weightlifting Ability of Robotic Manipulators

Sergy Stepura and Joshua Dayan
Technion – Israel Institute of Technology, Mechanical Engineering Faculty Technion City, Haifa 32000, Israel

Keywords: Open Chain Manipulator, Weightlifting, One-hand Snatch, Optimization, Minimal Energy Trajectory, Calculus of Variation, Genetic Algorithm, Line-Search, Motor Overload.

Abstract: In this position paper we concentrate on one aspect of the robot tasks, its ability to pick up and move heavy loads, far beyond the manufacturer instructions. Such expansions may apply to other tasks, as well. Three approaches to improve manipulators weightlifting ability are suggested: mimicking the Olympic weightlifter's strategy; weightlifting along the minimal energy trajectory and overloading manipulator's motors. The analytical analysis has been worked out on a simple pendulum. Three optimization methods were compared: calculus of variation, Genetic algorithm, Line-search. Then, the results were demonstrated on a model of the Mitsubishi RV-M2 manipulator. Combination of motor overloading with minimal energy trajectory yielded increase of weightlifting capability 10 times higher than the manufacturer specs.

1 INTRODUCTION

In most cases, industrial robots are made to perform limited tasks and the operational envelops, as specified by the manufacturer, are quite narrow and conservative. This way the mandatory safety is ensured and the system provides "reasonable" (but not optimal) and satisfactory performance at all times. However, in many cases, the operational envelop may be expanded substantially, without sacrificing safety, by introducing more sophisticated control and taking advantage of all DOFs, which are traditionally incorporated into the basic design, even if there is no real functional need.

In this paper we concentrate on one aspect of the robot tasks, i.e., its ability to pick up and move heavy loads, far beyond the manufacturer instructions (e.g., Wang et al., 2001). However, such expansions may apply to speed, manipulation, tracking, force applying and possibly other tasks, as well. The maximal allowable payload of most open chained robotic manipulators ranges between 5% to 20% of the manipulator's self-weight. Human beings are able to lift weights greater than their own body weight. This fact intrigues investigating the possibility of improving weightlifting ability of industrial manipulators.

Three approaches to improve manipulators weightlifting ability are suggested: mimicking the Olympic weightlifter's strategy (see Figure 1); weightlifting along the minimal energy trajectory and overloading the manipulators' motors.

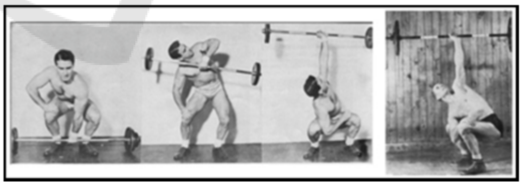

Figure 1: One-hand Snatch - Applying this technique, the human body acts similar to an open chain robotic manipulator (Matheson, 1996, Chen et al., 2009).

To obtain the minimal energy trajectory, three optimization approaches are suggested: analytical approach (Euler-Lagrange equation, Calculus of Variations); adaptive algorithm (Genetic Algorithm) and gradient based iterative approach (Line-Search). Among other researchers seeking optimal trajectory to improve manipulator's weight lifting ability are: Wang et al., (2001), Saravanan et al., (2007), Korayem and Nikoobin (2007) and Korayem et al., (2008).

Here, we studied a simple pendulum, i.e. a rod with an electrical motor connected to its upper tip. All three approaches lead to the same solution: oscillatory trajectory (swinging motion) increasing the amplitude up to the weight lifting completion.

There are differences among the three approaches, in accuracy, ease of constraints implementation, speed of solution convergence and

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selection of initial guess for the manipulator trajectory. For the latter, and specifically for industrial manipulators with many DOFs, it is suggested that the initial guess would be the reversal of the falling trajectory.

The recommended trajectory is demonstrated by simulation, using the model of the RV-M2 Movemaster made by Mitsubishi. In contrast to most of the researches dealing with manipulators weightlifting ability, the RV-M2 Movemaster is subject to operational constraints and is unable to perform free swings (oscillating movements) using its most powerful joints. Implementation of techniques for improving weightlifting capabilities for a manipulator with such limitation indicates that the suggested techniques are certainly applicable for a wide range of industrial manipulators, especially for those that have lesser limitation.

In this paper we show that implementation of any of the suggested techniques can substantially improve the weightlifting capabilities of the open chain robotic manipulator.

2 MIMICKING THE OLYMPIC WEIGHTLIFTER'S STRATEGY

Olympic weightlifting methods are described in many Internet sites. Several of them are:

http://tomgorman.moonfruit.com - Describes the Olympic lifts. Correct performance of the two classic lifts. Link to other lifts.

http://www.chidlovski.net/liftup - The Lift Up site is a personal tribute to Olympic weightlifting, to the Olympic weightlifting history and to its legends. The site is an author's project and it is a part of several web-based projects developed by chidlovski.com.

http://www.exrx.net - Exercise Prescription on the Net is a free resource for the exercise professional, coach, or fitness enthusiast.

There are some basic rules for successful weightlifting that can be obtained from contemplation on the Olympic weightlifting methods:

- To reduce energy consumption and improve stability, the weightlifting is performed close to the lifter center of mass.
- The initial momentum obtained by simultaneous work of all muscles.
- Most of the weightlifting is performed by the strongest muscles (lags and back muscles) while the hands are used only for the final tuning and stability control.

In the present work all these rules were accomplished while performing the weightlifting along the minimal energy trajectory.

3 WEIGHTLIFTING ALONG THE MINIMAL ENERGY TRAJECTORY

The study was performed on simple pendulum, i.e. a rod with an electrical motor connected to point A (Figure 1).

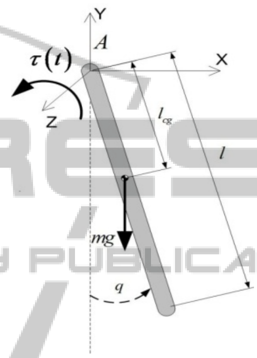

Figure 2: Scheme of the pendulum with its motor.

Optimization Rule

The trajectory $\tilde{q}(t)$ that minimizes the functional J_E is calculated in the next three equations (see Figure 2). Actually, $\tilde{q}(t)$ is the trajectory of minimal energy.

$$J_E\{q(t)\} = \int_0^{t_f} \left(\tau\left(q(t)\right)\right)^2 dt \tag{1}$$

Where t_f is the lifting time, $q(t)$ is any weight lifting trajectory and $\tau(t)$ is a torque applied by the electrical motor:

$$\tau(t) = I_p\ddot{q}(t) + c\dot{q}(t) + l_{cg}m_p g\sin\left(q(t)\right) \tag{2}$$

Where I_p is the pendulum moment of inertia (respective to the point A), c is a dynamic friction coefficient, m_p is the pendulum gross mass and g is the gravity and l_{cg} is defined in Figure 2.

The electrical motor energy consumption along the weightlifting trajectory is defined as:

$$E\{q(t)\} = \int_0^{t_f} \{(\tilde{I}(t))^2 \cdot R(t)\} dt \tag{3}$$

Where $\tilde{I}(t)$ is the electrical current along the weightlifting trajectory and $R(t)$ is the electrical resistance of the motor.

For most electrical motors installed in robotic manipulators the electrical resistance is almost constant and the electrical current is proportional to the torque. Thus, the value of the functional $J_E\{q(t)\}$ is proportional to $E\{\tilde{q}(t)\}$, the energy consumption of the electrical motor along the weightlifting trajectory.

Here, we verified that minimizing functional J_E also minimizes the maximal torque along the weightlifting trajectory (Figures 3 and 4).

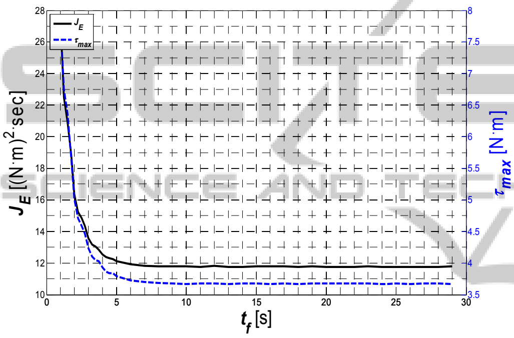

Figure 3: Value of the J_E functional and the maximal torque $\tau_{\max}$ vs. lifting time t_f.

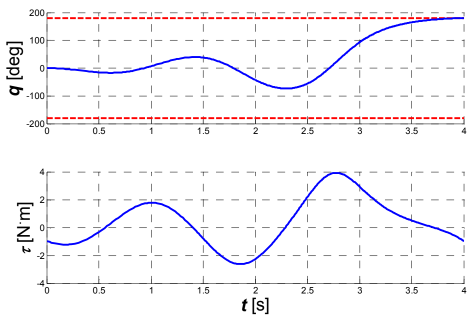

Figure 4: Minimal energy trajectory $q(t)$ and control torque $\tau(t)$ corresponding to lifting time $t_f = 4[s]$.

It is intuitively clear and can be calculated as well, that there is a lower bound for the energy consumption during weight lifting along minimal energy trajectories. However, it was found that there is an upper bound, as well (see Figure 5). This is correct if there is no coulomb friction in the joints, which obviously, is not always true.

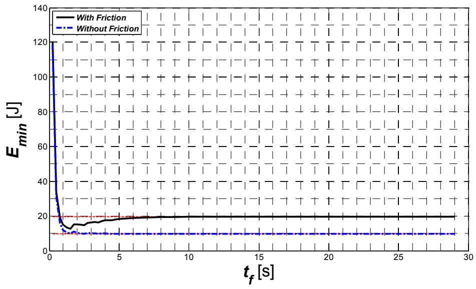

Figure 5: Minimal energy for pendulum lifting with and without friction vs. Lifting Time t_f.

Then, it can be concluded that if there is no demand for fast weightlifting (lifting within a specified interval of time) the energy consumption along the minimal energy trajectory is bounded as follows:

$$\Delta U_g < E_{\min} \leq 2 \cdot \Delta U_g \tag{4}$$

where, ΔU_g is the potential energy gained by the lift.

4 DETERMINING THE PREFERRED OPTIMIZATION METHOD

Three optimization methods were compared in the present study:

- **Calculus of Variations (CoV)** – Analytical method finding the boundary value problem who's solution minimizes the functional; this method is the most accurate of all three and can be used as a reference for the comparison.
- **Genetic Algorithm (GA)** – Optimization method that mimics the process of "natural evolution" (adaptive method).
- **Line-Search (LS)** – Optimization based on gradient method.

All three methods compared for accuracy and calculation time. Table 1 summarizes the study findings. For the comparison all parameters were graded from 1 to 3, where 3 is the best result and 1 is the worst.

Line-Search method is chosen for calculating the minimal energy trajectory for the RV-M2 manipulator. The main reason for that choice is that Line-Search yields the shortest calculation time, while differences in accuracy for all three methods are relatively small.

Line-Search method is chosen for calculating the minimal energy trajectory for the RV-M2

Table 1: Comparison of optimization methods.

Method	Accuracy	Calc. Time	Restrictions/ requirements
CoV	3	2	A: See below
GA	1	1	**B: None**
LS	2	3	C: See below

(Table 1 Continued): Restrictions/requirements
A: The weightlifting trajectories must be smooth functions.
B: None
C: Small change in the weightlifting trajectory causes only a small change in the cost function.

manipulator. The main reason for that choice is that Line-Search yields the shortest calculation time, while differences in accuracy for all three methods are relatively small.

However, Line-Search method is extremely sensitive to initial conditions. Initial guess should be close to the final solution (minimal energy trajectory), especially when the functional has multiple local minimums. Reversal of the free-fall trajectory is suggested to be used as the initial guess. In Figure 6 the Reversed Falling Trajectory (RFT) and the minimal energy trajectory calculated by the CoV method are compared. It can be seen that the reversal of the falling trajectory is very close to the minimum energy solution as obtained by the CoV method (considered the most accurate method).

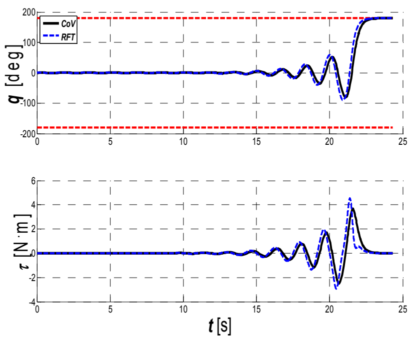

Figure 6: Comparison of $q(t)$ and $\tau_{\max}$ calculated by using CoV and Reversed Falling Trajectory (RFT).

5 MANIPULATOR MOTORS OVERLOADING

The third method of improving the weightlifting capacities of the robot is overloading the manipulator motors. Inasmuch as that the manipulator's manufacturer (Mitsubishi) does not provide information on the motors overloading abilities, specifications of the National Electrical Manufacturers Association (NEMA) were checked. According to NEMA the Service Factor defines the overload ability of the motor; as if it does not cause immediate damage to the motor, but only reduces its service life. A common value for the Service Factor of the electrical motors is between 1.15 and 1.5. (See also: Cowern, 2004, and Faulhaber Group Internet publication)

Usually, the electrical motors can sustain more than the Service Factor overload, but only for limited time. Not having information on the motors overloading capabilities the following assumptions were made for the maximal overload period and the minimal cooling time between overloads:

- The maximal overload period is one (1) second
- The minimal cooling time between the overloads is one (1) second

With the above assumptions of maximal overload period and minimal cooling time, it was found that substantial improvement of the weightlifting capabilities of the open chain robotic manipulator is possible by such motor overloading (see Table 2). In addition, it was obtained that for the RV-M2 manipulator the overload remains within the conventional Service Factor of 1.45.

Table 2: Comparison of improving weightlifting capabilities techniques.

Technique	Payload weight [kg]	Payload weight [%]	Notes
Manufacturer Spec.*	1.6	5.7%	A
Weightlifter's strategy	10	35%	B
Minimal energy trajectory	10	35%	
45% Motors overloading + Minimal energy trajectory**	15	53%	C

A: The manipulator weight is 28 kg
B: The technique applied when the weightlifting is performed along the minimal energy trajectory.
C: Satisfy the assumed constraints on maximal overload period and minimal cooling time.

6 DEMONSTRATING THE IMPROVEMENT OF THE WEIGHTLIFTING CAPABILITIES FOR THE MITSUBISHI RV-M2

In contrast to most of the works dealing with manipulators weightlifting ability (Wang et al., 2001), (Saravanan et al., 2007), (Korayem and Nikoobin 2007); (Korayem et al., 2008), the RV-M2 Movemaster, selected for the demonstration in this research, has mechanical limitations on most of its powerful joint's (Figure 7) and is unable to perform free swings (or, oscillating movements) with these joints. However, implementation of the techniques for improving weightlifting capabilities for manipulator with such limitations provides a stronger approval that the suggested techniques are applicable for wide range of industrial manipulators, especially for those that have fewer limitations.

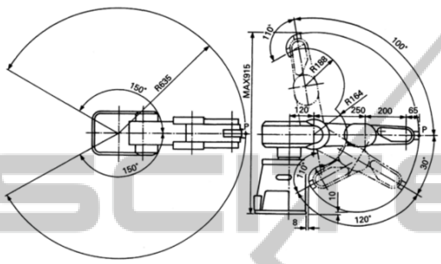

Figure 7: Mitsubishi RV-M2 Movemaster manipulator – Operation space

The dynamic model of Mitsubishi RV-M2 has been constructed and simulated by Matlab for demonstrating the improvement of the weightlifting capabilities.

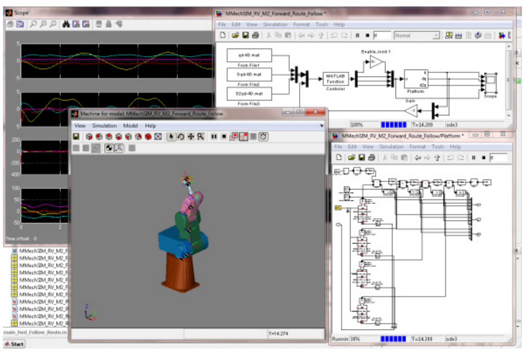

Figure 8: RV-M2 manipulator dynamic model and visualization.

For the demonstration of these capabilities improvement all three techniques were applied to the dynamic model described in Figure 8. To demonstrate the robustness of the suggested techniques the weight lifting was simulated with 0, 10 and 15 kg payloads; maximal payload without overloading the motors was calculated for 10 kg, while the 15 kg payload required the motors overloading (Figures 9, 10, 11 and 12 for the different joints). Animation demonstrating the simulation results is also available for all four joints.

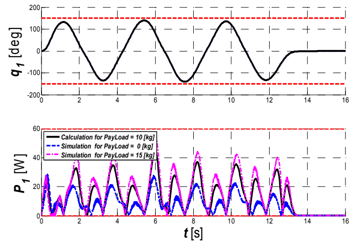

Figure 9: RV-M2 Joint #1 (Waist Joint).

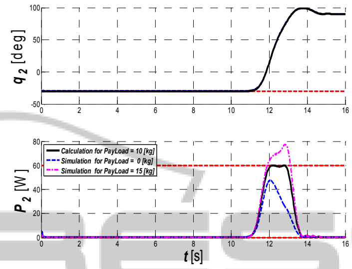

Figure 10: RV-M2 Joint #2 (Shoulder Joint).

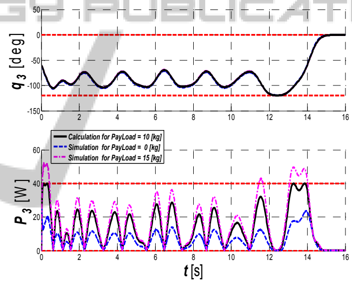

Figure 11: RV-M2 Joint #3 (Elbow Joint).

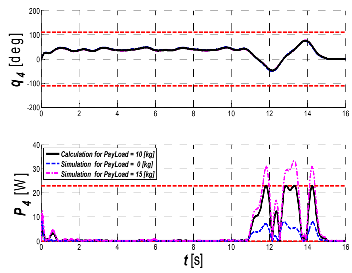

Figure 12: RV-M2 Joint #4 (Wrist Pitch Joint).

7 CONCLUSIONS

All three approaches suggested improving manipulators weightlifting ability, i.e., mimicking the Olympic weightlifter's strategy, weightlifting along the minimal energy trajectory and overloading the manipulators' motors, were shown to bring substantial improvement in the weightlifting capabilities of the open chain robotic manipulator. Just applying weightlifting strategy or, minimum energy trajectory, increases the robot ability to pick up load, which is seven times heavier than that specified by the manufacturer. Allowing tolerable overload of the motors raises the payload 10 folds. The suggested techniques are applicable for wide range of industrial manipulators, even those with motion constraints.

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