A Review on Optimization Methods to Enhance Energy Efficiency of Robots

G Lakshmi Srinivas, Ruturaj Mane and Arshad Javed

September 20, 2019

National Conference on Multidisciplinary Design, Analysis, and Optimization
22rd – 23rd, March 2019, MSRUAS, Bengaluru

A Review on Optimization Methods to Enhance Energy Efficiency of Robots

G. Lakshmi Srinivas[1], Ruturaj Mane[2] Arshad Javed[3]

[1 2 3] Department of Mechanical Engineering, BITS - Pilani Hyderabad Campus, Hyderabad, g.l.srinivas7@gmail.com

Abstract

The aim of this paper is to make available of a comprehensive review and to provide a reference of existing methodologies developed for enhancing of the energy efficiency of robots. In the present scenario of increased application of robots, the huge energy consumption is also being predicted. One of the possible solutions for energy consumption can be in terms of developing energy efficient robots. In the domain of energy efficient robot, different attempts are made in past, such as use of lightweight material, analysis of speed, identification of the least energy consuming trajectories and reduction of components weight by topology optimization, etc. The available methodologies to reduce the energy consumption of industrial robots are classified into two groups. The first group comprises of the different attempts of energy efficiency through trajectory optimization of the manipulator. Here, the energy required to perform a particular task is considered. The path is then optimized for minimum power consumption of the motors. This approach is applicable to task-specific cycles. The second group comprises the application of topology optimization method. Topology optimization approach is developed in the last decade and proved to be a promising approach for minimization of the mass of a structural member of machine component. Presented work will be helpful to understand the advancement in this domain.

Keywords: Topology optimization, Trajectory optimization, Energy efficiency, Robotics, Lightweight design.

1. Introduction

In the automation sector, the necessity of industrial robots is rising on account of their advanced superiority and productivity. According to the International Federation of Robotics (IFR) report 2018, industrial robot sales doubled over the past five years globally [1]. Out of different methods, trajectory and topology optimization approaches are reviewed because of its high improvement of energy efficiency. Trajectory optimization deals with the minimization of power consumption for an industrial robot. For this, optimization problem can be framed based on objective functions such as time to complete path, vibration, and energy consumption of robotic systems. Topology optimization deals with minimization of mass by creating holes in design space for an industrial robot. For topology optimization problem, minimum compliance is usually chosen as the objective function.

The paper is systematized as follows: In Section 2, the different trajectory optimization for enhancing energy efficiency is discussed. In Section 3, the main topology optimization approach for minimizing energy consumption is reviewed and conclusion is drawn in Section 4.

2. Trajectory optimization

The energy consumption of the robot is also decided by the path or trajectory made during a work cycle. In order to minimize the joint torque, different trajectories can be evaluated for an industrial robot. The trajectory optimization can be classified into two major domains, i.e., point-to-point trajectory and multi-point trajectory (or continuous path). For a trajectory defined by point-to-point (PTP) motion, end-effector moves from a start point to final point in the workspace. The path in this trajectory is made through a suitable interpolation method used by the master controller. PTP trajectory robots are employed for pick and place, palletization, and spot welding operations in the industry. The various methodologies developed considering PTP trajectory optimization is based on direct and indirect approach. In the case of direct approach, optimal control problem is converted into a nonlinear programming problem. The direct approach method can be solved in two steps. In step 1, trajectory optimization problem discretized directly by changing it into a constrained parameter problem known as nonlinear programming. In step 2, solve the nonlinear programming problem using a penalty function approach or methods of augmented or modified Lagrangian functions.

In the case of direct approach, the initial attempts were made by using nonlinear programming for trajectory optimization [2]. However, the level of accuracy from this method is lower and the issue of local minima is also observed. Recently, the energy consumption of robotic system considering motor losses and auxiliaries losses as a part of objective function were optimized for the improvement of energy efficiency [3 -5].

In the case of indirect or inverse approach, the trajectory optimization problem can be solved in three steps. In the first step, the necessary and sufficient conditions for optimality are defined. In second step, optimization problem is formed combining the objective function and constraints. Finally the optimization problem is solved using calculus of variations or maximum principle methods or numerical methods. In order to obtain very smooth motion and optimization process, a polynomial with a degree higher has to be chosen with respect to the number of imposed constraints [10, 14, 15, and 18]. However, higher increment in the degree of the polynomial does not lead to significant enhancement in energy saving [7], B-Splines has minimal support with the given degree of a polynomial [1, 11 and 16]. To obtain the coefficient of the polynomial in online trajectory planning genetic algorithm and real-coded genetic algorithm are used [6, 8, and 10]. As this method is efficient than direct method, it is also applied for different robotic systems [15-19].

Multi-point trajectory represents a continuous path (CP) approach, where end effector travels through intermediate points between start point and final point. Multipoint trajectories are used for applications such as welding, panting, quality inspection through moving camera, etc. Vibrational approach by inverse of Jacobian method minimizes the error in B- spline [20]. Focused collision avoidance path is generated by selecting cost function which gives a set of points joined with a suitable polynomial that gives smooth motion and minimum energy consumption [21]. A multi-objective function is used for minimum energy in B splines [22, 23]. Table 1 provides the important and recent developments in this domain. In this table, the various approaches to use trajectory optimization is presented with respect to algorithm used, trajectory profile type, number of DOF of the considered manipulator, its application and experimental validation status is provided.

Table 1: Point to point and multipoint trajectory optimization literature

Reference	Year	Algorithm	Trajectory Profile	DOF	Application	Exp.
Point to Point Trajectory optimization						
Field et al. [6]	1996	Genetic	B Spline-cubic	6	Industrial	Y
Bailón et al. [7]	2010	Real-coded genetic	8 D Polynomial	6	Industrial	N
Fung et al. [8]	2011	Real-coded genetic	8-12D Polynomial	-	LCD glass handling	N
Hsu et al. [9]	2011	Gradient based algorithm	12 D Polynomial	-	-	N
Hansen et al. [10]	2012	Inverse dynamic algorithm	B Spline	6	Industrial	Y
Hsu et al. [11]	2013	Particle Swarm optimization	7-30 D Polynomial	-	Toggle mechanism	Y
Hansen et al. [12]	2013	Real coded genetic	5 D & B-Spline	2	Industrial	Y
Fung et al. [13]	2013	Genetic algorithm	3-12 D Polynomial	-	-	Y
Wang et al. [14]	2018	Taguchi	6 D polynomial	-	Robot mini Quad	Y
Multi Point Trajectory optimization						
Hirakawa et al. [20]	1997	Steepest gradient method	B-spline	4	Industrial	Y
Sengupta et al. [21]	2011	Invasive weed optimization	Cubic polynomial	-	-	N
Fenucci et al. [22]	2016	Branch and bound	B-Spline	6	Industrial	Y
He et al. [23]	2016	Multi-Objective	B-Spline	6	Industrial	Y

3. Topology optimization

Topology optimization is an auspicious and efficient method to enhancing the energy efficiency of industrial robots. Topology optimization is a subdivision of structural optimization method useful for minimizing the material percentage in design space [24]. The design space is discretized by four node bi-linear square finite elements. The density-based modified solid isotropic material with Penalization (SIMP) approach is used for modeling material properties in a continuous setting through interpolation of 'λ_ϕ' as shown in equation 1. The modified SIMP interpolates Young's modulus of the material and permits a straight forward execution of sensitivity analysis as well as additional filters techniques [25].

$$\lambda_\phi(\rho_\phi) = \lambda_{\min} + \lambda_\phi^n(\lambda_o - \lambda_{\min}), \qquad \rho_\phi \in [0,1] \tag{1}$$

where 'λ_o' is stiffness of the design space, '$\lambda_{\min}$' is a small stiffness allocated to void regions for avoiding stiffness matrix from a singularity and 'n' is a penalization aspect incorporated to ensure the design space as solid or void. 'ϕ' is the design variable, 'ρ_ϕ' is element density. For topology optimization problem minimum compliance chosen as objective function as shown in equation 2. Compliance is Compliance is the reverse of stiffness, mechanically it represents the amount of strain energy stored in robotic link.

$$\begin{aligned} \min_z \ : \ & \mu(\phi) = \delta^T \kappa \ \delta = \sum_{z=1}^{N} \gamma_\phi(\rho_\phi)\delta_\phi^T \kappa_o \delta_\phi \\ Subjected\ to \ : \ & \nu(\phi)/\nu_o - \chi = 0 \\ & \kappa\delta - \tau = 0 \\ & 0 \le \phi \le 1 \end{aligned} \tag{2}$$

where 'χ'is the volume fraction, '$\mu(\phi)$' is the compliance, 'δ', 'τ' and 'κ'are the global displacement, force vectors, and global stiffness matrix, respectively, 'δ_z' is the element displacement vector, 'N' is the total number of elements, '$v(z)$' and 'v_o' are the material volume and design domain volume, respectively, finally 'γ_z' is the element stiffness matrix, 'κ_o' is the stiffness matrix. For illustration, topology optimization process of a single robotic link is given here with initial boundary condition. The mechanical member of 1 DOF fixed at one end whereas another end is subjected to force (F), as shown in Figure 1. The height and length of the mechanical member are 80 mm and 300 mm respectively. While it is rotating continuously, centrifugal forces (CF) come into picture and gravity (GF) pulls it always vertically downwards at the centroid of the design space. The initial design space subjected to the topology optimization problem. Some portions of the design space are kept free from topology optimization process to give feasibility for assembly and measurement purposes. Mathematical gradient code developed in MATLAB for above stated 1 DOF robotic arm. In each iteration of the process the topology changes thus the center of gravity (CG) also changes dynamically. In order to apply CF and GF subroutine is developed to capture CG point.

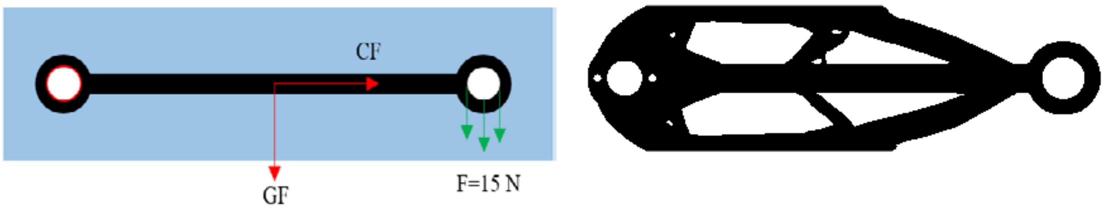

Figure 1: Design space before and after topology optimization

For realistic and accurate topology, mesh independency filter and grayscale removal filters are also included in the topology optimization routine. In order to confirm the accuracy of results, a mesh independency test is performed here. At grid size 2100 × 560 both Von-Mises stress and deflection values are converged as shown in Table 2. The link is considered to be made of mild steel (density 7700 kg/m3, Poisson's ratio 0.3, Young's modulus 200 GPa) with a volume reduction of 50% i.e. volume fraction of 0.5.

Topology optimization method gained popularity in the research community in late 1990. Significant research on the application of topology optimization on industrial robots was started in 2006. A few structural components of the 22 DOF humanoid were optimized for at least 30% reduction in mass experimentally by means of topology [26-28]. Further, the hydride multibody system, simulation analysis, and topology optimization approach was selected flexible bodies, objective function kept as maximization of mechanical stiffness and minimization of mass at least 15% [29-32]. Industrial serial robots of 6 DOF were optimized by multi-objective topology method for reduction of weight 7.1%, the applied load was analyzed dynamically, and this study was carried out by considering worst-cases of applied force [33, 34]. 5 DOF industrial robots were topologically optimized by SIMP approach considering static loading conditions for mass reduction of 44.4% [35-39]. Integrated optimal design approaches were used for 6 DOF serial industrial robots by use of part-level topology optimization and system level optimization for mass distribution in the design space [40, 41]. The actuating torque and dynamics was optimized by mass redistribution of 2 DOF planar robotic for mass reduction of 32.8% [42]. Recently topology optimization approach adopted to five bar mechanism of an industrial robot and ram structure of friction stir 6 DOF industrial welding robot for decrease the computational time and enhancing energy efficiency by reducing mass by 62.6% respectively [43,44].

Table 2: Mesh independency of Von-Mises stress and deflection at different grid sizes.

S. No.	Grid Size	Von-Mises stress (MPa)	Deflection (mm)	Time (min)
1	300 × 80	3.52	0.00967	0.43
2	600 × 160	3.34	0.00973	1.78
3	900 × 240	3.20	0.00974	4.58
4	1200 × 320	3.45	0.00976	8.51
5	1500 × 400	3.41	0.00978	13.82
6	1800 × 480	3.37	0.00980	21.07
7	2100 × 560	3.35	0.00980	26.18
8	2400 × 640	3.35	0.00980	39.51
9	2700 × 720	3.35	0.00980	52.25
10	3000 × 800	3.35	0.00980	56.57

4. Conclusion

The electrical power requirement is increasing in industrial sector with the application of robots. Various techniques and methodologies are proposed in this domain to reduce energy consumption. In the present paper, the available methodologies and prominent developments towards the reduction of energy consumption by the industrial manipulator were revised. The methodologies were grouped into the major domains. Conventionally the trajectory of a robot is focused to optimize the cycle time and energy consumption. In the recent year, topology optimization method is also proved as an important tool to achieve this objective. In this paper, the brief review of these two methodologies was summarized. In addition to the methodology, the optimization of a robotic link through conventional topology optimization was demonstrated. From the available literature is evident that topology optimization method help to save more power compared to the trajectory optimization method. Also, the cycle time of the process remains untouched. The present review will be helpful to choose and understand the methodologies that are used to reduce the energy consumption of an industrial robot.

5. Acknowledgments

The effort presented in this work is funded by the "Department of Science and Technology (DST) – Science and Engineering research board (SERB), India" (File Number: ECR/2017/000799), and Research Initiation Grant-BITS Pilani.

6. References

[1] International Federation of Robotics. Ifr.org: Global industrial robot sales doubled over the past five years https://ifr.org/downloads/press2018/2018-10-18_Press_Release_IFR_WR_2018_Industrial_Robots_ENG.pdf, Retrieved 18 October 2018.

[2] Hargraves, C. R., & Paris, S. W., Direct trajectory optimization using nonlinear programming and collocation. Journal of Guidance, Control, and Dynamics, 10(4), 338-342, 1987.

[3] Brossog, M., Bornschlegl, M., & Franke, J, Reducing the energy consumption of industrial robots in manufacturing systems. Journal of Advanced Manufacturing Technology, 78(5-8), 1315-1328, 2015.

[4] Richiedei, D., & Trevisani, A., Analytical computation of the energy-efficient optimal planning in rest-to-rest motion of constant inertia systems. Mechatronics, 39, 147-159, 2016.

[5] Abe, A., An effective trajectory planning method for simultaneously suppressing residual vibration and energy consumption of flexible structures. Mechanical Systems and Signal Processing, 4, 19-27, 2016.

[6] Field, G, and Yury, S., Iterative dynamic programming: an approach to minimum energy trajectory planning for robotic manipulators, In Proceedings of IEEE Robotics and Automation, 3, 2755-2760, 1996.

[7] Bailón, W. Pérez, E. Barrera Cardiel, I. Juárez Campos, and A. Ramos Paz, Mechanical energy optimization in trajectory planning for six DOF robot manipulators based on eighth-degree polynomial functions and a genetic algorithm, 7th International Conference on Electrical Engineering Computing Science and Automatic Control, 446-451, 2010.

[8] Fung, R. F., & Cheng, Y. H., Minimum-energy trajectory planning for an LCD glass-handling robot. In 2011 4th International Conference on Intelligent Networks and Intelligent Systems, 61-64, 2011.

[9] Hsu, Y. L., Huang, M. S., & Fung, R. F., Trajectory planning and control for precision positioning table driven by a PMSM. 2nd International Conference on Intelligent Control and Information, 26-31, 2011.

[10] Hansen, C., Öltjen, J., Meike, D., & Ortmaier, T., Enhanced approach for energy-efficient trajectory generation of industrial robots. IEEE - Automation Science and Engineering (CASE) 1-7, 2012

[11] Hsu, Y. L., Huang, M. S., & Fung, R. F., Energy-saving trajectory planning for a toggle mechanism driven by a PMSM. IFAC Proceedings, 46(5), 628-635, 2013.

[12] Hansen, C., Kotlarski, J., & Ortmaier, T., Experimental validation of advanced minimum energy robot trajectory optimization. 16th International Conference on Advanced Robotics (ICAR) (pp. 1-8), 2013.

[13] Fung, R. F., & Cheng, Y. H., Trajectory planning based on minimum absolute input energy for an LCD glass-handling robot. Applied Mathematical Modelling, 38(11-12), 2837-2847, 2014.

[14] Wang, L., Wang, C., Du, W., Xie, G., Song, K., Wang, X., & Zhao, F., Parameter optimization of a four-legged robot to improve motion trajectory accuracy using signal-to-noise ratio theory. Robotics and Computer-Integrated Manufacturing, 51, 85-96, 2018.

[15] Von Stryk, O., & Bulirsch, R., Direct and indirect methods for trajectory optimization. Annals of operations research, 37(1), 357-373, 2019.

[16] Fung, R. F., & Cheng, Y. H., Minimum-energy trajectory planning for an LCD glass-handling robot. In Intelligent Networks and Intelligent Systems (ICINIS), 61-64, 2011.

[17] Huang, M. S., Hsu, Y. L., & Fung, R. F., Minimum-energy point-to-point trajectory planning for a motor-toggle servomechanism. IEEE ASME Transactions on Mechatronics, 17(2), 337, 2012.

[18] Ayten, K. K., Sahinkaya, M. N., & Dumlu, A., Optimum trajectory generation for redundant/hyper-redundant manipulators. IFAC-PapersOnLine, 49(21), 493-500, 2016.

[19] Reiter, A., Gattringer, H., & Müller, A., Real-time computation of inexact minimum-energy trajectories using parametric sensitivities. In International Conference on Robotics, 174-182, 2017.
[20] Hirakawa, A. R., & Kawamura, A., Trajectory planning of redundant manipulators for minimum energy consumption without matrix inversion. In Proceedings of International Conference on Robotics and Automation, 2415-2420, 1997.
[21] Sengupta, A., Chakraborti, T., Konar, A., & Nagar, A., Energy efficient trajectory planning by a robot arm using invasive weed optimization technique. Third World Congress on Nature and Biologically Inspired Computing, 311-316, 2011.
[22] Fenucci, A., Indri, M., & Romanelli, F., An off-line robot motion planning approach for the reduction of the energy consumption. IEEE Emerging Technologies and Factory Automation (ETFA) 1-8, 2016.
[23] He, T., Zhang, Y., Sun, F., & Shi, X., Immune optimization based multi-objective six-DOF trajectory planning for industrial robot manipulators. In 2016 12th World Congress on Intelligent Control and Automation (WCICA), 2945-2950, 2016.
[24] Bendsøe, M. P., & Sigmund, O, Topology optimization: theory, methods and applications (2 Ed.). Berlin: Springer, 2003.
[25] Sigmund, O., Morphology-based black and white filters for topology optimization. Structural and Multidisciplinary Optimization, 33(4-5), 401-424, 2007.
[26] Albers, A., Brudniok, S., Ottnad, J., Sauter, C., & Sedchaicharn, K., Upper body of a new humanoid robot-the design of armar iii. In Humanoid Robots, 2006 6th IEEE-RAS International Conference, 308-313, 2006.
[27] Lohmeier, S., Buschmann, T., Schwienbacher, M., Ulbrich, H., & Pfeiffer, F., Leg design for a humanoid walking robot. In Humanoid Robots, 2006 6th IEEE-RAS International Conference, 536-54, 2006.
[28] Lohmeier, S., Buschmann, T., & Ulbrich, H., Humanoid robot LOLA. In Robotics and Automation, 2009. ICRA'09. IEEE International 775-780, 2009.
[29] Albers, A., Ottnad, J., Häußler, P., & Minx, J., Structural optimization of components in controlled mechanical systems. In ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 565-572, 2007.
[30] Albers, A., Ottnad, J., Weiler, H., & Haeussler, P., Methods for lightweight design of mechanical components in humanoid robots. In Humanoid Robots, IEEE-RAS International Conference, 609-615, 2007.
[31] Albers, A., & Ottnad, J., System based topology optimization as development tools for lightweight components in humanoid robots. 8th IEEE-RAS International, 674-680, 2008
[32] Liang, M., Wang, B., & Yan, T., Dynamic optimization of robot arm based on flexible multi-body model. Journal of Mechanical Science and Technology, 31(8), 3747-3754, 2017.
[33] Huang, H. B., & Zhang, G. The topology optimization for l-shape arm of Motorman-HP20 robot. In Applied Mechanics and Materials Trans Tech Publications, 201, 871-874, 2012.
[34] Chu, X. Y., Xu, H. H., Shao, G. F., & Zheng, W. F., Multi-objective topology optimization for industrial robot. In Information and Automation (ICIA), 2016 IEEE International Conference 1919-1923, 2016.
[35] Ghiorghe, A, Optimization design for the structure of an RRR type industrial robot. UPB Scientific Bulletin, Series D: Mechanical Engineering, 72(4), 121-134, 2010.
[36] Yunfei, B., Ming, C., & Yongyao, L., Structural Topology Optimization for a Robot Upper Arm Based on SIMP Method. In Advances in Reconfigurable Mechanisms and Robots II, 725-733, 2016
[37] Denkena, B., Bergmann, B., & Lepper, T., Design and optimization of a machining robot. Procedia Manufacturing, 14, 89-96, 2017.
[38] Junk, S., Klerch, B., Nasdala, L., & Hochberg, U., Topology optimization for additive manufacturing using a component of a humanoid robot. Procedia CIRP, 70, 102-107, 2018.
[39] Luo, H., Fu, J., Wang, P., Liu, J., & Zhou, W., Design optimization of the ram structure of friction stir welding robot. Mechanics of Advanced Materials and Structures, 1-11, 2019.
[40] Kim, B. J., Yun, D. K., Lee, S. H., & Jang, G. W., Topology optimization of industrial robots for system-level stiffness maximization by using part-level metamodels. Structural and Multidisciplinary Optimization, 54(4), 1061-1071, 2016.
[41] Wang, X., Zhang, D., Zhao, C., Zhang, P., Zhang, Y., & Cai, Y, Optimal design of lightweight serial robots by integrating topology optimization and parametric system optimization, Mechanism and Machine Theory, 132, 48-65, 2019.
[42] Gupta, V., Chaudhary, H., & Saha, S. K., Dynamics and actuating torque optimization of planar robots. Journal of Mechanical Science and Technology, 29(7), 2699-2704, 2015.
[43] Briot, S., & Goldsztejn, A., Topology optimization of industrial robots: Application to a five-bar mechanism. Mechanism and Machine Theory, 120, 30-56, 2018.
[44] Luo, H., Fu, J., Wang, P., Liu, J., & Zhou, W., Design optimization of the ram structure of friction stir welding robot. Mechanics of Advanced Materials and Structures, 1-11, 2019.