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Inverse Kinematics Problems in Industrial Robotics: A Review

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Abstract

Over the last few decades, human activity in many fields is supported or replaces by robots, with use of industrial robots can be seen worldwide and has significantly increased with a faster increasingly trend. Majority of the problems reported in the industry survey and literature are dealing with path planning and robot control parameter optimization. In this competitive industrial environment there is ardent need to make industrial robots more flexible and adaptable, following are the areas identified: path planning optimization for redundant robots operating in environment of obstacles; Smooth trajectory generation; optimization of robot control parameters in manufacturing process; Multi-objective optimization to improve overall performance of industrial robot with respect to above mentioned issues.

Keyords: Redundant manipulators, Inverse kinematics, degree of freedom,

1. Introduction

Robot manipulator is an electromechanical device that requires human dexterity to perform a variety of tasks. A common characteristic of such applications is that the robot needs to operate in unstructured environments rather than structured industrial work cells. Motion control and trajectory planning for robots in unstructured environments pose important challenges due to uncertainties in environment modeling, sensing, and robot actuation. With the advancement of various technologies, the scope of the tasks performed by robots is widened so that it is desirable for machines to extend the capabilities of men and to replace them by robots in carrying out at tiresome as well as hazardous jobs. In order to accomplish the tasks in human-like ways and to realize a proper and safe co-operation between humans and robots, the robots of the future must be thought of having human excellence in terms of its structure, intelligence, smartness and reactions. Therefore, a robot operating under some degree of autonomy can be extremely complex electromechanical systems whose analytic description requires advanced methods.

In most of the manufacturing applications, these robots have to perform the tasks under the conditions of restrictions. Therefore motion control of manipulator movements in an environment with obstacles is a critical issue. This control of motion is achieved by solving the inverse kinematics of the redundant manipulator with obstacle avoidance. The main issue in solving the inverse kinematic problem of a redundant manipulator lies in the fact that they are highly nonlinear and there exist multiple solutions. In the case of a redundant manipulator, the number of inverse kinematic solutions may become infinite and closed form solutions are impossible to find in general. The kinematics of the rotational robot is more difficult to analyze than the linear robot. In order to develop a scheme for controlling the motion of a manipulator, it is necessary to develop techniques for representing the position of the arms at points in time.

2. Industry survey and Literature reviewed

Changes in national and international competition, coupled with the mass application of new technologies, are revolutionizing production. Consumers are demanding quality, and manufacturers are being forced to provide it. Companies that wish to remain competitive and maintain their market share are turning to such advanced technologies as computer-aided industrial robots. One of the biggest challenges that they face today is the flexibility and adaptability of robots in manufacturing functions & cost that is required to build a robot.

Manufacturing Industries nearby were surveyed to know the practical difficulties encountered during manufacturing and support activities. Manufacturing Industries nearby were surveyed to know the practical difficulties encountered during manufacturing and support activities.

Potential areas identified from Industry survey:

- Path planning optimization for laser welding and arc welding.
- Precise control of robot for finishing of complex components.
- Minimization of jerk i.e. smooth trajectory generation by minimizing acceleration
- Path planning using machine vision system for obstacle avoidance.
- Multi-tasking robot and flexible path planning.
- Optimization of process parameters for various applications of robots in manufacturing
- Requires Programming flexibility & adaptability as part changes
- Redundant manipulators to resolve the task of the automatic assembly and demounting of the complex equipment repair, and works which cannot effectively perform manually.

Majority of the problems reported in the industry survey are related to dealing with path planning and robot control parameter optimization.

Various researchers have used different approaches to solving the inverse kinematic problem of the redundant manipulator in the environment of obstacles.

Klein et al.(2015) considered the problem of the inverse kinematics of redundant robots in environments with moving obstacles. The problem is formulated as an optimization problem under the constraints of multiple goals: a primary goal described by the end-effectors trajectory and a secondary goal describing the obstacle avoidance criteria. Parker et al. (1989) introduced the use of genetic algorithms for solving the inverse kinematics problem of redundant robots. The genetic algorithm was used to position the end-effector of a robot at a target location while minimizing the largest joint displacement from the initial position. Won et al.(1996)applied Powell's method for predetermined optimal redundancy resolution for a redundant manipulator. A method based on genetic algorithms was introduced to solve the problem of inverse kinematics of redundant robot manipulators in environments with obstacles. Nearchou and Aspragatos (1996), formulated problem as a constrained optimization problem with the main objective being the minimization of the end-effector's positional error, and secondary objective considered is the satisfaction of the constraints related to obstacle avoidance. A technique to manage constraints in the genetic search in order to maintain feasibility has been presented. The efficiency of the proposed algorithm was demonstrated through multiple experiments carried out on a seven-DOF robot manipulator. The algorithm guarantees the collision-free movement of the robot producing an acceptable positional error. Shugen and Kobayashi (2000) proposed an obstacle avoidance control scheme for the Moray arm which is based on the 2-DOF Moray drive control method and the posture space analysis. The 2-DOF Moray drive control derogates the control problem of the hyper-redundant degrees of freedom (DOFs) to the simple one of 2 DOFs: one of the control variables signifies the linear combination of the objective initial and final postures of the arm, while another one expresses the amount of the pull-out-displacement when pulling the arm out of the housing slider. The obstacle collision-free trajectory is generated for the Moray arm by analyzing a defined posture space that is determined by the above-stated two variables. Zha et al.(2002) presented a unified approach to optimal pose trajectory planning for robot manipulators in Cartesian space through a genetic algorithm. A genetic algorithm is used to choose the parameters (coefficients) of space curves such that the pose ruled surface and its area and area change ratios are optimized for achieving good kinematics and dynamics performances. According to Kalraet.al. (2006) the kinematics equations of an industrial robot are non-linear and transcendental in nature. Their inverse kinematics solution provides the joint angles that are required to attain a particular position of the robot wrist in the robot workspace. The inverse kinematics solution may provide multiple robot configurations that all achieve the required goal position of the manipulator. In the absence of obstacles, the robot configuration closest to the current robot configuration in the joint space may be selected. He also suggested that evolutionary approach based on a genetic algorithm, which is utilized as the optimization strategy for their work. The success of a genetic algorithm for a specific optimization problem depends on the basic mechanism used to represent an individual in the population. When a binary coding is used for continuous search space, a number of difficulties arise. One difficulty is the Hamming cliffs associated with certain strings, from which a transition to a neighboring solution in real space requires the alteration of many bits. Hamming cliffs in the binary coding cause artificial hindrance to a gradual search in the continuous search space. In binary-coded GAs, a large string length should be chosen to achieve a greater precision in the solution. For large strings, the population size requirement is also large, thereby increasing the computational complexity of the algorithm. A careful thinking of the schema processing in binary strings reveals that not all of Holland's schemata are equally important in most problems having continuous search space. For a continuous search space, the meaningful schemata are those that represent the contiguous regions of the search space. Real-coded Gas is thus more suitable for continuous search spaces. Here an individual is characterized by a vector of real numbers. The researcher obtains better results by applying real coded GA, however, obstacles are not considered in this work.

Mirosław et al. (2006) addresses the problem of controlling a redundant manipulator with state and control dependent constraints. The task of the robot is to followed by the end-effector a prescribed geometric path given in the task space. The control constraints resulting from the physical abilities of robot actuators are also taken into account during the robot movement so that a solution to the aforementioned robot task exists, the Lyapunov stability theory is used to derive the control scheme.

Taha(2006) proposes the process of programming industrial robots, which is divided into two major levels: trajectory planning and trajectory control. The first consists of determining the time history of the robot kinodynamic parameters (position, velocity, acceleration, effort) that correspond to the desired task. The second consists of converting these computed parameters into control signals in order to command the actuators during the execution of the task and to compensate for any deviation. The first category concerns tasks involving motions along a prescribed geometric path and corresponds, for example, to continuous welding, glowing, flame cutting or deburring operations. The second category concerns tasks requiring point-to-point (or free) motions involved, for example, in pick and place operations such as loading and unloading of belt conveyors, tools changes in machine-tools, and simple assembly operations. For the first category, the problem of trajectory planning is relatively easy to solve because the path is already specified needs only to find the best way to follow it. In contrast, in the second category, the problem is equivalent to the search of a good path and the best manner to follow it, which is more complex.

Despite the fact that this method is very elegant and allows the resolution of a large number of motion planning problems, it has several drawbacks:

The trajectory being directly derived from the robot dynamic model the resulting equation is a complex combination of non-linear functions. Since the trajectory must be calculated systematically during the tracking process, the burden of real-time computation is significantly increased.

Maria et al. (2012) combined genetic algorithm with two approaches firstly with a closed loop as CLGA to solve discontinuous, not differentiable, stochastic, or highly nonlinear problems and then with an open loop as OLGA for comparison with a genetic algorithm. Swagat et al. (2010)used online inverse-forward adaptive scheme with a KSOM (Kohonen self-organizing map) based hint generator for solving the inverse kinematic problem of a redundant manipulator. In this approach, a feed-forward network such as a radial basis function (RBF) network is used to learn the forward kinematic map of the redundant manipulator. This network is inverted using an inverse-forward adaptive scheme until the network inversion solution guides the manipulator end-effector to reach a given target position with a specified accuracy. The positioning accuracy, attainable by a conventional network inversion scheme, depends on the approximation error present in the forward model. The proposed inverse-forward adaptive scheme effectively approximates the forward map around the joint angle vector provided by a hint generator. Thus the inverse kinematic solution obtained using the network inversion approach can take the end-effector to the target position within any arbitrary accuracy. But, an accurate forward map would require a very large size of training data as well as network architecture. However, this approach requires resolving the redundancy, with complex mathematical equations. But with the help of the Simulated annealing, the end effector need not requires resolving the redundancy.

Mihahi et al. (2012) provided the methodology of inverse kinematics and obstacle avoidance for complex unknown environments, with multiple obstacles in the working field. Q-learning is used together with neural networks in order to plan and execute arm movements at each time instant. The algorithm developed for general redundant kinematic link chains has been tested in the particular case of Power Cube manipulator.

Significant research is reported in the literature by Rao and Pawar (2011) that the traditional optimization methods such as Powell's method, Fletcher-Reeves method, dynamic programming, and the reduced gradient method etc. have been used for this class of problems. However, these traditional methods of optimization do not fare well over a broad spectrum of problem domains. Moreover, traditional techniques may not be robust and they tend to obtain a locally optimal solution. Considering the drawbacks of traditional optimization techniques, attempts are being made to the model and optimize the complex problem using new techniques. The most commonly used non-traditional optimization technique is a genetic algorithm. Genetic algorithm operates on a population of potential solutions by applying the principle of survival of the fittest to achieve an optimal solution. The genetic algorithm can begin with a population of solutions in parallel, but it suffers from poor convergence properties. Hence, there is a need to use more recent and robust method for optimization of control parameters of robot redundant manipulator. Particle swarm optimization (PSO) is reported to be the better algorithm for optimization. Particle Swarm Optimization is also one of the nontraditional technique for optimization of the nonlinear functions and complex problems with good convergence properties.

Gómez et al.(2012) addressed the problem of planning collision-free paths for hybrid robots. In particular, the authors proposed a procedure for computing optimal trajectories in presence of obstacles. The procedure is based on combining a quick random search algorithm (RRT) with a genetic algorithm. Tadej and Leon (2013) proposed a control method for kinematically redundant robots with a smooth continuous transition between different tasks. The method is based on null-space formulation. Conditions for the tasks design are given using the Lyapunov-based stability discussion.

Huang et al. (1993) proposed an inverse kinematic solution of 6-DOF robot manipulator using the immune genetic algorithm. In this work forward kinematic formulation is presented using DH-algorithms. End effector displacement error based fitness function is used for implementation of proposed algorithm and results obtained through adopted technique are compared with the neural network back propagation algorithm.

Bernal et al. (2013) proposedmetaheuristic algorithm application in robotics. In this work, Ant Colony optimization algorithm and genetic algorithm are used for path planning of robot manipulators end effector.Kumar et al. (2010) proposed an inverse kinematic solution of redundant manipulator using the Lyapunov method. In this work, the optimization approaches to solve an inverse kinematic problem which is converted into a nonlinear problem solved by the Lyapunov method. An improved energy based function is determined for the optimization. Xu et al. (2014) proposed inverse kinematic of the 4-DOF redundant manipulator using two different optimization criteria. First optimization criteria are the minimization of extra redundant DOF and other criteria are based on total potential energy minimization of manipulator links. They have developed numerical optimization method for calculating the trajectory planning computation which is a bit more expensive. Therefore to overcome this computation cost a sequential quadratic programming and iterative Newton-Raphson method is used. Mazhari and

Kumar (2008) proposed kinematics and dynamics solution of PUMA 560 robot manipulator using a genetic algorithm, simulated annealing, and generalized pattern search methods. They have designed a controller for PUMA manipulator using above adopted algorithms. Fine tuning is requiring for the controller to achieve desired speed of simulations

Rokbani and Alimi(2013) proposed an inverse kinematic solution of 2-DOF robot manipulator using particle swarm optimization algorithm. In this work initial position and desired position error based objective function is used which is also known as the Euclidean distance norm for the end effector. In this approach norm, the analytical solution of forward kinematic is presented which is later used in the objective function of PSO algorithm.

Stevo et al. (2014) proposed an inverse kinematic solution of 6-DOF ABB IRB 6400FHD robot manipulator using a genetic algorithm. In this work forward kinematic equation is generated by using DH-algorithm which is later used to obtain fitness function for the genetic algorithm. In this work displacement error of end-effector from point to point, the motion has been calculated through adopted method. The objective function containing three separate parts which are energy function, operation time and position accuracy to get combined fitness function for the genetic algorithm. Albert et al. [2008]proposed an Inverse kinematic solution of 3-DOF revolute robot manipulator using the real-time genetic algorithm. In this work end-effector displacement from its initial point to the desired point has been optimized using a genetic algorithm..

From the literature review, it is cleared that, for Inverse kinematics problem of redundant robot manipulator under the conditions of restrictions, there is the strong need to develop methodology and optimization program, which will be able to consider any general configuration i.e. any number of links and any number of obstacles as input.

Thus significant research reported in the literature that use robots' redundancy to solve the inverse kinematics problem in environments with obstacles as show in Table 1. In the various industrial applications and operations, robotic manipulator has to tackle the obstacles while performing the desired task, therefore the solution to such inverse kinematic problem in the presence of obstacles becomes more complex. The researchers applied different algorithms like a genetic algorithm, particle swarm optimization, KSOM and also some of the traditional techniques like sequential quadratic programming, reduced gradient method etc.

Shortcomings identified from the literature review:

• Sensory-based system leads to increase in the cost of robots and reduced reliability.

• A method of industrial robot layout based on operation sequence optimization.

• To deal with low production volumes and high product mix i.e. is adaptability & flexibility

• Limitations imposed by conventional methods of inverse kinematics. The manipulator having a higher number of DOFs increases mathematical complexity and decreases the efficiency due to a decrease in position accuracy and power transmission.

• Most of the researchers had considered inverse kinematics problem but without considering obstacles, while few researchers considered the same with a limited number of obstacles.

• Most of the researchers had applied traditional methods of optimization for solving this problem. However, as the traditional method usually converges to the local optimum solution while solving the complex multimodal problem. Recently, the researchers are also attempting to apply evolutionary algorithms like genetic algorithm (GA) and particle swarm optimization (PSO) etc to deal with various issues such as collision avoidance, process parameter optimization, singularities etc. But these methods also suffer from drawbacks like poor convergence, no guaranteed convergence to global optimum solution, and difficulty in determining the algorithm control parameters. Hence better solutions of the above mentioned issues can be obtained by using more powerful algorithms.

The web-based survey of Robotics news bulletins, robotic reviews from experts, online advance robotics issues, robotics and autonomous systems, chronicles among the other is conducted to get acquainted with the current scenario of industrial robots and to investigate the areas of research.

Significance in Context of Current Status

As we know that for kinematic analysis, rotational, translational, DH algorithm and homogeneous matrices have shown their importance in the application of positional analysis of different manipulators. From many decades these methods have been adopted by various researchers and implemented in a different number of manipulators. However, ensuring the absence of proper mathematical formulations with less computational and mathematical cost which leads to decreasing in many applications, where quick calculations are required. These techniques fail to prove when the manipulator having a higher number of DOFs. In general when there is higher DOF manipulator the inverse kinematic formulations are much more difficult due to nonlinear, time varying and transcendental functions. There are many other tools and techniques are available to solve the inverse kinematic problem, for example, algebraic, Jacobian, or geometric, analytical, pseudo inverse Jacobian etc. These methods are conventional and they do not provide an exact solution. On the other hand, the alternative of these techniques for representing and solving kinematics problem are quaternion algebra, Lie algebra, exponential algebra, epsilon algebra and screw theory which are being used for many years due to less mathematical operations.

Considering the complexities involved in the process of modeling and consequently solving the inverse kinematic problem for achieving precise, optimized and faster solution for the real-time application. The present research problem in design, the research issues will primarily focus on selecting/developing an appropriate tool for achieving the objectives after validating them on various configurations of industrial robots.

On the other side of these conventional techniques, intelligent or soft computing techniques are widely used to find out the inverse kinematic solutions. This intelligent technique includes artificial neural network, hybrid ANN, fuzzy logic, hybrid fuzzy, metaheuristic algorithms and biologically-inspired approaches. In past decades, many others have adopted this technique because of their less computational and mathematical cost. These techniques are useful when the manipulator having a higher number of DOFs were generally conventional method fails. So the ultimate aim is to find out an inverse kinematic solution using these techniques and to develop a novel method for resolving the inverse kinematic problem for any configuration of the robot manipulator.

3. Conclusion

A survey on complex inverse kinematics problems in industrial robots is presented in this paper. Developing robust solutions for solving complex inverse kinematics problem related to manufacturing engineering is a key issue to deal with various aspects like path planning optimization, smooth trajectory generation and optimization of robot control parameters. Although few attempts have been made to resolve these issues, it is revealed from literature review and industrial survey that accuracy, robustness and cost effectiveness are still remaining issues in which improvement can be sought.

REFERENCES

[1] Maciejewski A. A and C. A. Klein, "*Obstacle Avoidance for Kinematically Redundant Manipulators in Dynamically Varying Environments*," Int. J. Robot.reserach, vol. 4, no. 3, pp. 109–117, 2015.

[2] Won H Chung M. G and Choi B, "*A Numerical Method of Predetermined Optimal Resolution for a Redundant Manipulator*," IEEE Trans. Robot.Autom., vol. 9, no. 2, pp. 215–220, 1993.

[3] Nearchou A. C and Aspragathos N. A., *"Point-to-point motion of redundant manipulators*," Vol. 31, no. 3, pp. 261–270, 1996.

[4] Zha X. F., "*Optimal pose trajectory planning for robot manipulators*," Mech. Mach. Theory, Vol. 37, no. 1, pp. 1063–1086, 2002.

[5] R. VenkataRao , P.J. Pawar, "*Parameter optimization of a multi-pass milling process using non-traditional optimization algorithms"* Applied Soft Computing Vol. 10, 445–456, 2010

[6] Kalra K. A., Mahapatra P.B., and Agarwal D.K. "*An evolutionary approach for solving the multimodal inverse kinematics problem of industrial robots,"* Mechanism and Machine Theory, vol. 41, no. 2, pp. 1213–1229, 2006.

[7] Geometricpath constraints," Mechatronics, vol. 16, no. 3, pp. 547–563, 2006.

[8] Swagat Kumar, LaxmidharBehera ,McGinnity T.M., *"Kinematic control of a redundant manipulator using an inverse-forward adaptive scheme with a KSOM based hint generator"*Robotics and Autonomous Systems, Vol.58 pp.622-633, 2010

[9] Joey K. Parker,Ahmad R. Khoogar, *"Inverse Kinematics of Redundant Robots using Genetic Algorithms"* IEEE, vol.1, pp. 271-279, 1989

[10] Maria da Grac¸ Marcosa, TenreiroMachadoa, T.-P.Azevedo-Perdicoúlis, "*A multi-objective approach for the motion planning of redundant manipulators".* Applied soft computing, vol.12, pp. 589-599, 2012

[11] S. Kumar, L. Behera, and T. M. Mcginnity, "*Kinematic control of a redundant manipulator using an inverse-forward adaptive scheme with a KSOM based hint generator*," Rob. Auton.Syst., vol. 58, no. 5, pp. 622–633, 2010.

[12] Gómez-Bravo F, Carbone G., and Fortes J. C., "*Collision free trajectory planning for hybrid manipulators,"* Mechatronics, vol. 22, no. 1, pp. 836–851, 2012.

[13] Huang H, S. Xu, " *Hybrid Taguchi DNA Swarm Intelligence for Optimal Inverse Kinematics Redundancy Resolution of Six-DOF Humanoid Robot*," Math. Probl.Eng., vol. 2, 2014.

[14]Bernal A, "*Meta-Heuristic Optimization Techniques and Its Applications In Robotics."http://dx.doi.org/10.5772/54460, 2013.*

[15]Shugen Ma, Isao Kobayashi, "*An obstacle avoidance control scheme for the "Moray arm" on the basis of posture space analysis"Robotics and Autonomous Systems, vol. 32 pp. 163–172, 2000*

[16]Mihai Duguleana Florin Grigore Barbuceanu, Ahmed Teirelbar, Gheorghe Mogan *"Obstacle avoidance of redundant manipulators using neural networks based Reinforcement learning"*

[17] Robotics and Computer-Integrated Manufacturing Vol. 28, pp.132–146, 2012

[18] Xuan F. Zha*, "Optimal pose trajectory planning for robot manipulators"* Mechanism and Machine Theory Vol.37 pp.1063–1086, 2002

[19] MirosławGalicki "*Path-constrained control of a redundant manipulator in a task space"* Robotics and Autonomous Systems, Vol. 54 pp. 234–243, 2006

[20] TadejPetric, Leon Zlajpah, "*Smooth continuous transition between tasks on a kinematic control level: Obstacle avoidance as a control problem*",Robotics and Autonomous Systems, Vol. 61, pp. 948–959, 2013.

[21] TahaChettibi "*Synthesis of dynamic motions for robotic manipulators with geometric path constraints*".Mechatronics Vol. 16, pp. 547–563 2006.

[22] S. Mazhari and S. Kumar, "*PUMA 560 Optimal Trajectory Control using Genetic Algorithm, Simulated Annealing and Generalized Pattern Search Techniques*", World Academy of Science, Engineering and Technology, pp. 800–809, 2008.

[23] N. Rokbani and A. Alimi, "*Inverse Kinematics Using Particle Swarm Optimization, A Statistical Analysis*", Procedia Eng., vol. 64, pp. 1602–1611,

[24] 2013.

[25] Y. C. Albert, S. P. Koh, S. K. Tiong, C. P. Chen, and F. W. Yap, *"Inverse Kinematic Solution in Handling 3R Manipulator via Real-Time Genetic Algorithm"*, International Symposium on Information Technology, 2008.

[26] S. Števo.Sekaj and M. Dekan, "*Optimization of Robotic Arm Trajectory*

[27] *Using Genetic Algorithm*",The International Federation of Automatic Control, Cape Town, South Africa. August 24-29, 2014.

[28] http://www.robotics.gatech.edu/research

[29] https://www.sciencedaily.com/releases/2016/11/161107110346.htm