Path-based Optimal Design Strategy for Customized Redundant Manipulators

Ekta Singla, Satwinder Singh, Rohit Paul Kuruvilla, Bhaskar Dasgupta

Abstract

The rapidly growing range of robotic applications has resulted into the increased adoption of *customized manipulators*. This paper addresses the need for an optimization strategy that handles both the design and the path-planning of a robot, simultaneously, to fulfil the requirements of given tasks for a robotic application. The strategy will involve treating the path-planning and the robot design as coupled problems, as they are in reality, rather than treating them as separate stages in the robot development process for an application. This can be looked at as a superior approach to path planning that involves modifications in the underlying robot's design to optimize the output.This can also be looked at as a smarter robot design process in which the final path is not rigid, and can be altered to optimize given criteria. The work is focused at the robotic applications that involve cluttered environments and possesses the need of highly redundant manipulators. The proposed performance criteria is related to robot safety while maneuvering an optimal path. For non-redundant manipulators, focus is more on singularity avoidance and kinematic conditioning. Similarly, for a non-cluttered environment, a performance criterion related to robot safety would not be ideal. A novel performance index - $RoboGin$ is proposed in this paper that relates to collision avoidance and fits as basis for redundant manipulator design in cluttered environments. A case study have been presented to illustrate the significance and application of the proposed strategy, resulting into an optimal set of robotic parameters along with the optimal path.

Keywords: Robot Safety, Task-based design, Performance indices, Redundant manipulators

1 Introduction

To measure the performance of a manipulator, it is important to focus upon the application it is designed and applied for. The selection of a performance index plays a

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crucial role in *customized design* of a manipulator for any new application and/or in the selection of a manipulator out of existing available configurations. For the task-orientated robotic designs for cluttered environments, the requirements are normally related to the reachability at the required locations, obstacle avoidance and fulfilling of an optimality criteria (design objective(s)). To follow a fixed planned path/trajectory can be one of the design objectives, or once the robot is determined, its motion is planned for given tasks. This paper presents an integrated approach which caters both the path-planning problem and the robot synthesis, simultaneously. Since the robotic manipulator needs to be designed for specific tasks in fixed environments, e.g. maintenance of nuclear plants and/or inspection of coal-mines, such an integrated approach would result into a solution appropriate from a larger perspective — a more reliable guideline for the development of a task-based robot.

A path-based performance measure *RoboGin* is presented in this paper, with an aim of acquiring *comprehensive performance* from the required robotic arm, to work in a constrained environment with *maximum margin*. The measure is described in detail, along with its utilization as design objective, in optimal design of manipulators for given environments. The implementation of the strategy is illustrated through a robot design problem solving for a cluttered workspace. Section 2 presents the related works and the motivation to take up this work. Problem is defined in section 3. Section 4 defines and describes the proposed measure, which becomes the basis of the optimal design problem formulated in section 5.

2 Task-based Designs: Background

The foremost issues concerned with the optimal design of a task-based customized manipulator is to decide the *optimality criterion* signifying the overall expectations from the desired manipulator. A lot of research [1, 2, 3] in this area was focused on isotropic designs of articulated hands, grippers, closed kinematic chains or robotic arms — including *redundant manipulators*. Paredis and Khosla [4] introduced the aspect of *task-based robotic design* and presented a manipulator design strategy for prescribed end-effector locations. Similar and extended works had been presented later by many other researchers (e.g. refer [5, 6]), involving the performance indices based on the manipulator's Jacobian charateristics.

In the beginning of the 20th century, many researchers (refer [7, 8]) worked for the optimal design of fundamental robot manipulators for different objective criteria as minimizing torque over the entire trajectory, or maximal work volume and minimum link-lengths within prescribed limits. Recently, Carbone et al [9] presented an optimal design algorithm for multiple objectives, suitable for both serial and parallel manipulators. In general, the design attempts are based on the kinematic conditioning of the manipulators, which depends upon the local information concerned with the particular configuration only. For the task-based manipulator designs, it is more important to present the 'requirement(s)' of the manipulator in a comprehensive way. Recently, such task-based design criteria are appropriately utilized in surgical robot designs [10, 11] for minimally invasive robotic systems. A general strategy involving the design of a manipulator based upon the overall working in an environment is worth paying attention. This work is an attempt towards the integrated approach assistive in providing an *optimal* solution satisfying all the major requirements for developing a manipulator for given tasks.

3 Problem Definition

Given a fixed cluttered workspace and all the task space locations (TSLs) to be worked upon, a robotic manipulator is required to be synthesized along with its optimized path for maneuvering the environment while working at given locations. Either only position or even orientations can be prescribed for the working locations. All the robotic parameters (D-H parameters) are considered as design variables for a large solution space. The number of degrees of freedom (dof) are provided *a priori* in this work.

The objective of the design problem is to maximize the safety of the robotic manipulator from any collision with the workspace obstacles while following a path — optimally planned for that specific robot. The fulfillment of this objective requires the generation of a path corresponding to the robotic candidate determined in each iteration. This implies that a plath planning methodology is required to be an inherent part of the objective function evaluation during the optimal design procedure. Since the TSLs are prescribed in Cartesian coordinates and the planned path serves in joint space, an inverse kinematic strategy would be required to convert the TSL locations into the joint space locations, corresponding to each design candidate. Fig. 1 presents the complete problem structure.

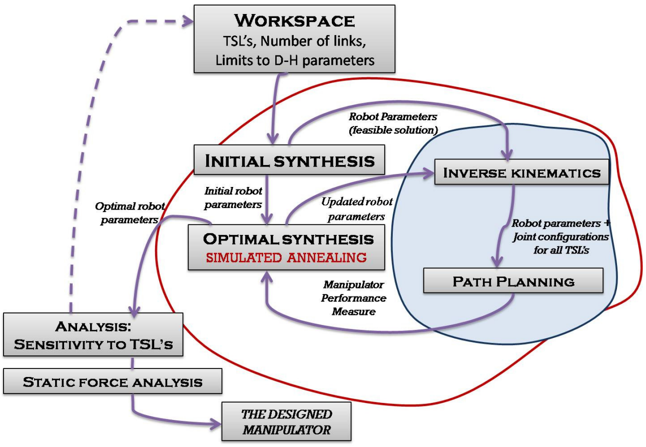
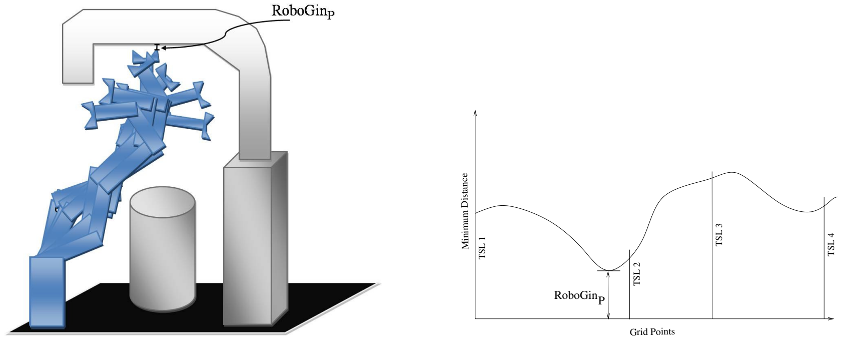


Figure 1: The Problem Structure



(a) The minimum $RoboGin_C$ of a manipulator while traversing a path

(b) Illustration of $RoboGin_P$ through minimum distance diagram.

Figure 2: The performance measure: $RoboGin$

4 $RoboGin_P$: a path-based performance measure

The focus of the design is on the capability of the manipulator to operate between the prescribed TSLs in the best sense. This can be incorporated through a performance index which reflects the uncertainties involved at different stages of design and development of a manipulator, in particular the inaccuracies in the 3-D model of a working environment. The proposed measure, named as *RoboGin*, derived from "robot margin", is defined as — *the minimum margin between the robot and the obstacles or among the links.*

For a particular joint configuration, the measure is represented as $RoboGin_C$, which signifies the closest distance of the robot links to the obstacles at a specific posture. The definition of the measure for a complete path of the manipulator is an extension of $RoboGin_C$ and is represented as $RoboGin_P$ as represented in Fig. 4[a]. A set of configurations present a path to be followed by a robot and similar to this, there may be another set of robot parameters which may result into another optimal path for the same task. The parameters corresponding to the larger value of $RoboGin_P$ is reported better out of the two sets.

5 Design Problem Formulation: Maximizing $RoboGin_P$

A design optimization problem is defined as the determination of an optimal set of robotic parameters, within the prescribed limits, which can provide maximum *RoboGin* while performing in the given workcell through the specified task space locations. The methodology is applicable for even kinematically redundant manipulators, required for highly cluttered environments.

5.1 Design variables

All the D-H parameters of a robotic arm are taken as the design variables. The *joint variables* change with the configuration corresponding to each TSL and so are counted N times, as $q_{11}, q_{12}, \cdots, q_{1n}; q_{21}, q_{22}, \cdots, q_{2n}; \cdots; q_{N1}, q_{N2}, \cdots, q_{Nn}$ where q represents either θ or d, according to the type of the corresponding joint as revolute or prismatic, respectively. The design variables which remain fixed for all configurations are $[a_1, a_2, \cdots, a_n;\ \alpha_1, \alpha_2, \cdots, \alpha_n;\ d_i$ (for revolute joint) or θ_i (for prismatic joint) for $i = 1, 2, \cdots, n]$. Parameters a_0 and α_0 are taken as zero for all cases. In all, there are $[(3 + N) * n]$ design variables for a problem of n links for reaching N TSL's.

5.2 Objective function computation

The algorithmic steps to compute the objective function $RoboGin_P$ with each new candidate robot (robotic parameters) are as follows.

TSLs in joint space (inverse kinematics): Determine the joint configurations for all the TSL's (N in number) using *optimal* inverse kinematics (IK) procedure. The IK problem is handled as an optimization problem with the objective as maximization of $RoboGin_C$, with joint parameters as the variables. This signifies the selection of the configurations with the maximum margin between the robot and the environment. The kinematic equations (for reachability of the end-effector at the Cartesian positions) are incorporated as equality constraints.

Path planning between each pair of TSLs Paths need to be planned between each pair of working locations. For N TSL's, $(N - 1)$ paths would be developed. In this work, the planner presented by Singla and Dasgupta [12], in joint-space, has been incorporated.

Critical margin Compute the critical distance ($RoboGin_P$) for the total path planned. This is the maximum $RoboGin_C$ out of all the configurations constituting the path.

It is worth noting here that each function evaluation includes N executions of the inverse kinematics routine and $(N - 1)$ executions of the path planning routine. Due to the involvement of large amount of computation, the number of function evaluations is an important constraint in the selection of the optimization algorithm.

5.3 Constraints handling

The manipulator design problem formulated as the optimization problem is supposed to handle the constraints listed ahead. It is worth mentioning here that the description for the computation of these constraints is not a part of this paper, and the reader can refer [13] for the details. The constraints are

1. the bounds over the design variables,
2. the constraints due to obstacle avoidance, and

3. the reachability of the end-effector at all the desired TSL's, with the kinematic condition of the manipulator within the prescribed limit.

The evaluation of the objective function needs the planning of the complete path between the TSL's which further requires the execution of the inverse kinematics routine to obtain joint configuration for each TSL. This process involves the feasibility checking associated with all the constraints enumerated above. This signifies that, during the iterative process of the problem solving technique, the feasibility checks are incorporated before the evaluation of the objective function which keeps the search for the optimal solution *within* the feasible region and does not allow any move towards infeasibility.

5.4 Problem solution: Simulated Annealing (SA)

The optimization problem formulated in the previous section is highly constrained, in particular due to the presence of equality constraints. Each function evaluation involves further solutions of optimization problems. Any method which needs large number of function evaluations may not be suitable for the situation. Besides, due to the unstructured solution space, the descent based techniques may not progress much and may stay stuck in close neighborhood of the initial solution itself. In this scenario, the process of simulated annealing provides a good trade-off between the two aspects. It is recommended to start the process with a *feasible solution*. For the purpose, an initial synthesis solution is determined for reachability, using the procedure described in [13]. Needless to mention, the negative of the objective '$RoboGin$' is used for minimization in the optimization formalism.

6 Case study: Results and discussion

This case study is included to present the manipulator synthesis for a realistic environment, as presented in Fig. 3(a). A robot is required for this cluttered room with 3 specified TSL's ($[140, 70, 50]$,$[120, 100, 30]$ and $[30, 120, 80]$). The number of links are taken as 8, with all joints as revolute. The base point of the manipulator is fixed at $(60, 30, 50)$. The initial D-H parameters are presented in Table 1 and the three configurations are shown in Fig. 3(b). Figs. 3(c) and 3(d) presents the paths for P_1–P_2 and P_2–P_3.

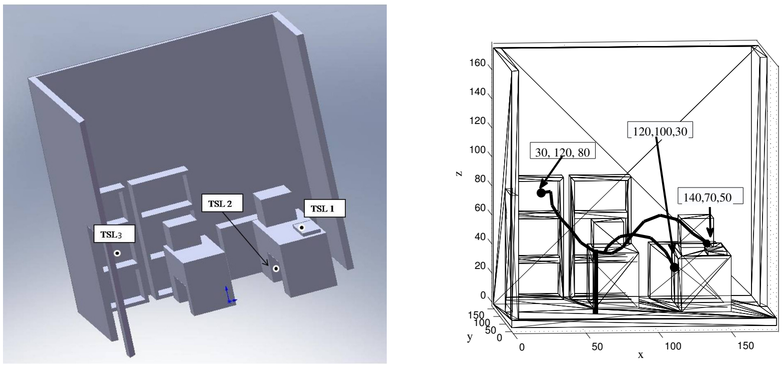
The initial robotic parameters are optimized using SA technique, for maximizing $RoboGin_P$. Table 2 provides the optimized results, including the robotic parameters and the three configurations. Comparison of the objective function for the initial and the optimal designs is presented in Fig. 4(a). The intermediate function values, with respect to the successful iterations of SA, are plotted in Fig. 4(b), showcasing the pattern of maximizing the function.

Table 1: Synthesis result: D-H parameters of an 8-link manipulator for a room environment.

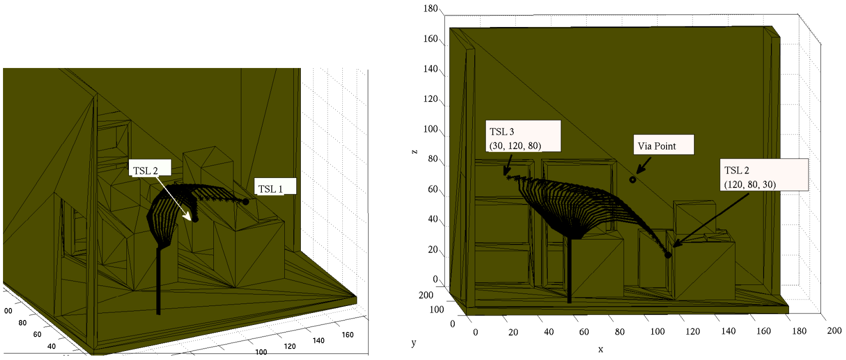
Link	*Twist* (α_i)	*Link Length* (a_i)	*Offset* (d_i)
1	0.58	14.4	-0.9
2	0.87	15.0	-2.8
3	0.99	14.5	-1.5
4	1.01	12.3	1.3
5	0.33	11.2	3.7
6	0.77	12.9	3.0
7	0.98	14.0	1.5
8	-1.01	14.6	-0.1

Table 2: Optimal robot parameters of 8-link manipulator for the room environment.

Link	*Link Length* (a_i) in $cm's$	*Twist* (α_i)	*Offset* (d_i) in $cm's$	*TSL1* (q_{1_i})	*TSL2* (q_{2_i})	*TSL3* (q_{3_i})	*TSL4* (q_{4_i})
1	14.7	0.56	-1.3	0.54	0.97	0.77	1.37
2	15.3	0.86	-2.7	0.39	0.33	0.82	0.93
3	14.2	0.99	-1.6	0.44	0.06	0.71	0.32
4	12.3	0.98	1.3	0.58	0.30	0.63	0.15
5	11.5	0.35	3.4	0.67	0.54	0.66	0.30
6	13.1	0.75	2.7	0.70	0.58	0.73	0.41
7	14.3	0.99	1.1	0.62	0.52	0.71	0.44
8	15.0	-0.99	-0.2	0.55	0.48	0.64	0.47



(a) A room environment (b) Robot configurations for the three TSLs

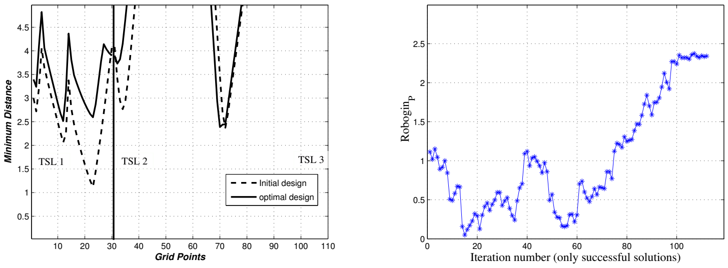


(c) Path planned betwen TSL-1 and TSL-2 (d) Path planned betwen TSL-2 and TSL-3

Figure 3: Optimal synthesis results for a 8-link manipulator

7 Conclusions

A path-based performance index ($RoboGin$) is proposed in this paper which signifies the minimum margin between the robot links and the obstacles, while traversing a planned path. An optimization problem is formulated in this paper with the objective function as the maximization of $RoboGin_P$, to maximize the safety of the robot while maneuvering the path. It has been illustrated how the important aspects of collision avoidance, reachability at the required TSL's, kinematic condition at the working postures and the joint limits are taken as constraints in the formulated optimization problem. The method of simulated annealing has been used for the solution of the formulated problem. The successful results confirms the suitability of the proposed measure in improving the quality of the solution in designing task-based manipulators for cluttered workspaces.



(a) Comparison of the objective function for the initial and the optimal designs.

(b) $RoboGin_P$ values plotted against the successful iteration numbers.

Figure 4: Optimized $RoboGin_P$ results

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