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A unified approach for performance analysis of randomly generated robotic morphologies☆

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Summary An attempt is presented towards a unified approach to compute kinematic performance of planar manipulators with the links connected in series, in loops and in combinations of both. The motivation of this work lies in the fact that serially connected links are normally selected for large manipulability and parallel manipulators are utilized for better stiffness. To acquire a topology suitable for a given task, the topological parameters can be considered variables in a manipulator design problems. However, since the complete kinematic model changes with each small change in the basic structure, a unified approach is important to work upon. A case of five-bar mechanism consisting of 2-degrees-of-freedom (dof) system is considered to demonstrate the proposed approach for performance analysis.
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Introduction

Kinematic synthesis is primarily concerned with the determination of the dimensions of the geometric parameters and the feasible range of the actuated joint variables, leading to, optimizing a nonlinear objective function and subject to a set of constraints. The performance evaluation strategy of any manipulator, say an open-chain, close-chain or a combination of both required the kinematic model of the structure. To evolve a design for any given requirement, and to keep the basic topology also as a design variable, a unified performance evaluation approach is required.

Various researchers have worked upon the optimization and analysis of hybrid manipulators for given tasks, considering a particular basic morphology to begin with. Kim (2006) studied the kinematics and dynamics of a 2-dof five-bar mechanism, which possesses low power dissipation, a simplified dynamics and a large structural stiffness due to both of its motors at base. Works have been reported in which a hybrid linkage is utilized as the basic morphology (Waldron et al., 1989; Cheng, 1994; Bera and Samantray, 2011; Singh et al., 2015) and various analyses for kinematic and dynamic performance have been carried out. However, no work and/or guidelines are available for the selection of a hybrid combination for a given task.

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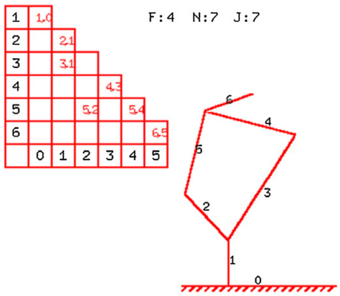

Figure 1 Randomly filled manipulator assembly matrices representing two different candidates.

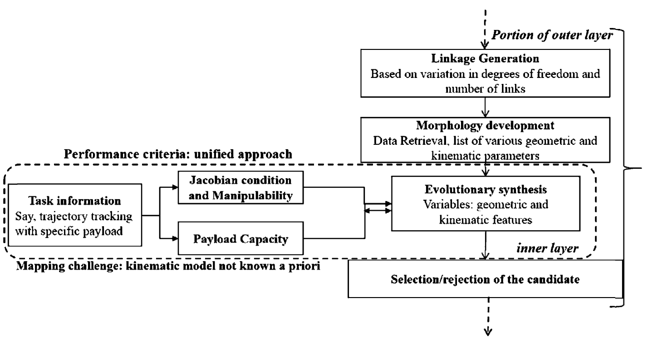

Figure 2 Proposed strategy for task-based morphology design of robotic manipulator.

Inspired by the evolutionary robotics concept (Lipson and Jordan, 2000), an attempt is made towards the evolution of basic hybrid morphology which is optimally suitable for given tasks. A large set of robotic manipulator linkages are randomly generated using a mechanism assembly matrix (Gupta and Singla, 2015). Fig. 1 presents an outcome by considering degrees of freedom, F as 4 and number of links, N as 7. Many such morphologies are considered possible candidates for performing a given task. However, the challenge lies in developing a common strategy for their performance evaluation and comparison.

This paper is an attempt towards a unified approach, as briefed in Fig. 2, for kinematic evaluation of the randomly generated morphologies, performance criteria considered are condition number (Klein and Bruce, 1987) while reachability at specified TSLs is considered as constraints.

Problem formulation

Working towards the aim of developing a common approach for performance analysis of randomly generated robotic morphologies with any number of dof, the problem objectives can be stated as:

(1) To obtain the loop closure equations of the robotic manipulator by taking the lengths and active angles as variables, while the remaining inactive angles (passive joints) may be computed from the system equations.
(2) To optimize all the system variables for the mechanism considering condition number as objective function.

It is planned to take a case of five-bar mechanism having 2-dof, which is to be optimized for minimum condition number over its domain.

Methodology

In Klein and Bruce (1987), the authors presented an algorithm for randomly generated planar robotic manipulators with the help of Mechanism Assembly Matrix (MAM) as shown in Fig. 1. It is planned to consider the mechanism as a system of coupled loop closure equations and solution of these equations will help in computation of various performance indices of the manipulator. In this paper, a closed loop five-bar planar manipulator has been considered for developing the loop-closure equations in ''*Loop closure equations*'' section. ''*Performance criteria*'' section is devoted to the computation of performance criteria to be optimized with Genetic Algorithm.

Loop closure equations

A five-bar planar mechanism is presented in Fig. 3 assuming its lengths l_1 to l_5 and all joint angles considered in anti-clockwise direction from x-axis marked with θ_1 to θ_5. It is well-known that for a five-bar mechanism there is a requirement of two dof and in this problem we are assuming θ_3, θ_4 as active joints. All other joints θ_1, θ_2, θ_5 are unactuated joints. Two angles θ_1 and θ_2 can be expressed in terms of θ_3 and θ_4 as $\theta_1 = \theta_1(\theta_3, \theta_4)$ and $\theta_2 = \theta_2(\theta_3, \theta_4)$. It is observed that as the mechanism is fixed along X-axis which result for angle θ_5 as 180° always. Loop closure equation for this mechanism given as

$$l_1 \cos\theta_1(\theta_3, \theta_4) + l_2 \cos\theta_2(\theta_3, \theta_4) + l_3 \cos\theta_3 + l_4 \cos\theta_4 + l_5 \cos\theta_5 = 0 \quad (1)$$

$$l_1 \sin\theta_1(\theta_3, \theta_4) + l_2 \sin\theta_2(\theta_3, \theta_4) + Ll_3 \sin\theta_3 + l_4 \sin\theta_4 + l_5 \sin\theta_5 = 0 \quad (2)$$

The angles θ_1 and θ_2 have been determined by solving Eqs. (1) and (2) using Hybrid Levenberg—Marquardt Algorithm (Moré, 1978) considering l_1 to l_5, θ_3 and θ_4 as variables.

Performance criteria

Condition number is taken as the objective function to be minimized in the optimization problem. This performance index is computed with the following steps.

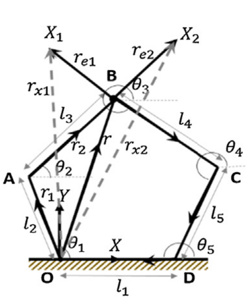

Figure 3 Five-bar mechanism with error vectors from TSLs.

Table 1 Condition number minimization of five-bar planar manipulator.

Run	l_1	l_2	l_3	l_4	l_5	θ_3	θ_4	C
a.	55.6615	69.7948	64.1443	64.1433	52.6331	43.1970°	313.2009°	1.0
b.	81.0581	62.1151	44.1097	44.1097	16.7190	127.7944°	217.7939°	1.0

Compute the end-effector position
From the Fig. 3 it is clear that by considering the path OAB, the vector sum of r_1 and r_2 will provide the resultant position vector r of the end-effector, which is computed as

$$\begin{Bmatrix} X \\ Y \end{Bmatrix} = \begin{bmatrix} l_1 \cos\theta_1(\theta_3, \theta_4) + l_2 \cos\theta_2(\theta_3, \theta_4) \\ l_1 \sin\theta_1(\theta_3, \theta_4) + l_2 \sin\theta_2(\theta_3, \theta_4) \end{bmatrix} \tag{3}$$

Compute Jacobian
From Eq. (3) Jacobian (gradient) is computed considering θ_3 and θ_4 as independent variables as

$$J = \begin{bmatrix} -l_1 \sin\theta_1(\theta_3, \theta_4)\dfrac{\partial\theta_1}{\partial\theta_3} - l_2 \sin\theta_2(\theta_3, \theta_4)\dfrac{\partial\theta_2}{\partial\theta_3} & -l_1 \sin\theta_1(\theta_3, \theta_4)\dfrac{\partial\theta_1}{\partial\theta_4} - l_2 \sin\theta_2(\theta_3, \theta_4)\dfrac{\partial\theta_2}{\partial\theta_4} \\ l_1 \cos\theta_1(\theta_3, \theta_4)\dfrac{\partial\theta_1}{\partial\theta_3} + l_2 \cos\theta_2(\theta_3, \theta_4)\dfrac{\partial\theta_2}{\partial\theta_3} & l_1 \cos\theta_1(\theta_3, \theta_4)\dfrac{\partial\theta_1}{\partial\theta_4} + l_2 \cos\theta_2(\theta_3, \theta_4)\dfrac{\partial\theta_2}{\partial\theta_4} \end{bmatrix} \tag{4}$$

In Eq. (4), the differential components $\frac{\partial\theta_1}{\partial\theta_3}, \frac{\partial\theta_2}{\partial\theta_3}, \frac{\partial\theta_1}{\partial\theta_4}, \frac{\partial\theta_2}{\partial\theta_4}$ are needed to be computed from the loop-closure equations by formulating a set of linear equations. An algorithm has been developed to automatically compute all the differentials of the loop-closure equations. After placing their values in Eq. (4), Jacobian matrix is computed.

Computing condition number
The condition number is the measure of the dexterity of a manipulator posture. It indicates the uniformity of the Jacobian transformation with respect to the direction of joint rates (Klein and Bruce, 1987). It is a local performance index and computed from eigenvalues of the Jacobian.

$$\text{Condition number, } C = \frac{\sigma_{max}}{\sigma_{min}} \tag{5}$$

Results and discussion

To study the formulation developed in this section, we have considered five-bar planar manipulator. The algorithm based on above formulation is implemented to compute performance criteria, which is taken at a fitness function in GA.

Fig. 4 represents the results obtained for the minimum value of condition number and the values of variables for optimized condition number are given in Table 1.

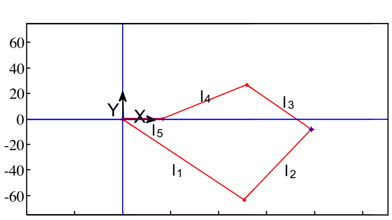

Figure 4 Minimized condition number results.

It is observed that the algorithm based on presented formulation is capable of providing the optimized results for the five-bar mechanism. The approach developed here is a step towards unifying the performance analysis approach for randomly generated planar robotic structures.

Conclusion

Task evaluation criteria are described for normally used manipulator topologies and illustrated through a parallel connected structure. The work finds its importance in providing a unified approach for performance evaluation of generated topology of any degree of freedom (dof) planar mechanisms. The work is an attempt towards the inclusion of topology selection in the task-based optimal designs of manipulators.

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