Population generation and validation for the task-based morphology evolution of robotic manipulators

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Abstract

An algorithmic platform is proposed in this paper to randomly generate and validate a set of basic morphologies of planar robotic manipulators, with combinations of serially connected links and loops. To design a robot for specified tasks of following a trajectory and possessing a prescribed stiffness, there are possibilities of working with several hybrid morphologies. Normally, one such basic morphology is selected with experience and the robot is designed for the given tasks. In the present work, basic structures of planar robotic manipulators are generated randomly, while varying the number of links and number of degrees of freedom (dof), within a stipulated number of links. This set will serve as an initial population for the evolution of an optimal mechanism for given tasks, using evolutionary algorithms. A novel concept of Mechanism Assembly Matrix has been introduced to *randomly* generate planar hybrid manipulators. The proposed algorithm is executed for various number of links and dof. The resultant structures are successfully matching to the possible solutions for the given number of links and the dof. The second phase involves the scrutiny of generated morphologies for validity and retain only the viable structures in the database. A brief discussion is included on the morphology selection during the process of task-based design of a robot.

Keywords: Hybrid manipulators, Initial population generation, Morphology synthesis, Evolutionary robotics

1 Introduction

The basic morphology of a robotic manipulator signifies its structural features in the form of connectivty of links and the number of degrees of freedom. In industry, most of the robots consist of open kinematic chains with all their links connected in a series. A parallel manipulator is a closed-chain mechanism having its two platforms (normally a fixed base and a moving platform) connected together by at least two independent kinematic chains. Both these types of basic morphologies, serial or parallel, have different utility/functionality. Serial manipulators are preferred for large dexterous workspaces, e.g. to manipulate in highly constrained environments. In situations, where the accuracy, high speed and stiffness are more relevant, parallel manipulators

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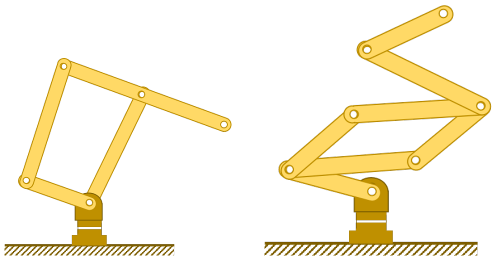
are considered as alternatives. The parallel manipulators possess high stiffness and large load capacity but suffer from a limited workspace. There are some of the tasks which require both — a large workspace and high payload capacity. For fulfilling such task requirements related to both dexterity and payload capacity, it is recommended to use hybrid manipulators. With various combinations possible for the basic morphology of a manipulator, even with a particular number of degrees of freedom, the generation of the possible morphologies and their selection criteria needs further attention. This work is an attempt towards the development of an assistive interface, to provide a guideline for the selection of the basic morphology of a *planar* hybrid manipulator, with respect to given tasks.

2 Background

Various researchers have worked upon the optimization and analysis of robotic mechanisms for given tasks, considering a *particular basic morphology* of the manipulator. To work on the selection of the basic morphology of a manipulator, an investigation of various existing mechanisms/manipulators are carried out. Some of the works involving hybrid morphologies have been selected as references and as target cases for this work. These combinations have been included in the pattern study for developing algorithms for random generation, evaluation criteria and selection of basic morphologies.

Kim [1] studied the kinematics and dynamics of a two degrees-of-freedom mechanism consisting of five bars as illustrated in Fig. 1(a). This manipulator possesses low power dissipation, a simplified dynamics and a large structural stiffness, since both of its motors are at base. In another work [2], the positional error is modeled for a planar manipulator with a closed loop induced in an open chain, as shown in Fig. 1(b), for the purpose of calibration based on linearization of the constraint equations. Bera et al. [3] modeled a planar hybrid manipulator on the basis of Stewart platform's architecture. Only three legs of Stewart platform are considered in a plane and connected with a platform at the top. Two legs at one joint and one leg at the other end of the platform is considered, with all joints as revolute. A tool placed at the top will have some confined trajectory. The characteristics of the mechanisms that affect the performance of a robot have been discussed by McCarthy [4]. Tsai [5] provide the mathematical relations between various performance criteria viz. mechanical structure of a robot, its workspace and mechanical advantage.

It is observed that there are possibilities of incorporating closed loops in serial mechanisms for improved robotic performance. Inserting one or more loops in the serial structure and augmenting a parallel mechanism with serial end-effectors are the morphologies worked upon by a number of researchers. Most of these works involve a specific morphology of the manipulator, which is thoroughly studied for its kinematics, dynamics and other application aspects. No discussion is available in any of the works about the basis of selection. A generalized platform has been proposed in this work for assistance in finding out how many variations can be generated for a specified dof and how to compare their performance. Inspired by the evolution of articulated robots using vertices, bars, neurons and actuators, presented by [6, 7, 8], the authors have made an attempt to develop a strategy for randomly generating planar hybrid



(a) (b)

Figure 1: Target basic morphologies: (a) Five-bar chain mechanism with two degrees of freedom, (b) Close loop within serial chain

manipulators. The major challenges of the work relate to the random generation of various morphologies and a common performance evaluation platform for randomly generated structures.

3 Problem Formulation

Working towards the aim of developing an assistive platform for the task-oriented selection of basic morphology for a planar hybrid manipulator, the objectives of this initial phase are as below.

1. To randomly generate the variations in the possible morphologies with maximum number of links. For this, a stipulated range of degrees of freedom will be considered and all the possible variations in manipulators with links connected in series and/or loops need to be explored. A concept of an assembly matrix, possessing the size equivalent to the number of links is utilized, for the purpose.

2. To provide an algorithmic framework for retrieval and collection of the morphology information from the randomly filled assembly matrix. This mainly consists of the connectivity of links and the location of active joints.

4 Methodology

The robotic manipulators are built up of rigid links connected with joints to provide various combinations. In this proposed methodology, the morphology of a planar manipulator(with revolute joints) is represented in the form of a matrix. With N representing the number of links, a $N \times N$ square matrix is named as *Mechanism Assembly Matrix* (MAM). It is considered that each joint, connecting two links, is represented by an element in the mechanism assembly matrix. Each cell of the matrix signifies a joint between the row indexed link and the column indexed link, leading to symmetry with respect to the leading diagonal. To gain computational efficiency, it is necessary to use the lower diagonal matrix and to eliminate other redundant entries. Based upon the assumption in subsection 4.1, the mechanism assembly matrix have been filled with flags randomly. The subsection 4.2 presents the algorithm developed for generation of basic morphology of planar hybrid manipulator.

4.1 Assumptions

Following assumptions are made for the random generation of robotic structures, with the help of proposed mechanism assembly matrix.

1. Each filled matrix element represents a joint/connection between the 'i' (index of row $link_i$) and 'j' (index of column $link_j$)
2. All joints are revolute and possess single dof each.
3. For any given number of degrees of freedom, represented as F in this work, the number of links needs to be more than F.
4. There will be a maximum of two more links connected at each node of a link. This assumption is just to reduce the complexity of a system in this initial phase.

4.2 Algorithm

This subsection represents the algorithm in two major parts. First is to generate the initial population of hybrid manipulators, in the form of mechanism assembly matrix. The data representing the mechanism assembly matrix is stored in the form of a link-list. The final list contains all the links along with their coordinates. In second part, the links connectivity is retrieved and portrayed using openGL.

4.3 Prior information retrieval

After the random generation of an initial pattern, in the form of the mechanism assembly matrix, it is required to retrieve the required information on links connectivity and the location of the active joints; along with the kinematics and geometric features. This will help in estimation of performance criteria for the mechanism. This section deals with the retrieval of the information, and deals with the base of the mechanism, the location of active joints and the point of application of force.

Base: It is assumed initially that the link number 1 must be connected to link number 0. This link number 0 will be base of the mechanism. Fig. 2 represents the schema for the fixation of the base.

Active joints: To randomly assign the active joints, each pattern is separated into succession of loops, started from the base. As the number of dof of the mechanism is known, the active joints can be assigned by fulfilling the loop constraints at each level and moving upward for another loop as shown in Fig. 2. For triangular loops, no active joint is allocated, and the procedure moves further for the next upper loop, for the assignment of active joints. In case of two legs starting from the base or from some other link, then the active joint can be assigned corresponding to any of these

Algorithm 1 Initial population generation algorithm for Mechanism Assembly Matrix

for given F, N calculate the number of joints, $J = \frac{3(N-1)-F}{2}$
generate an initial node $(0, 1)$ of a linked-list ▷ joint between $link_1$ and $link_0$
set $k = 0$
while $k < J - 1$ **do**
  generate a set of random numbers as (i, j), where $0 \leq i, j \leq N$ ▷ i: rows and j: columns
  check the set of random numbers for the following constraints:

1. $i > j$ ▷ Lower triangular matrix must be filled
2. (i, j) is a unique set ▷ Only distinct joints need to be flagged
3. count i, j from linked-list count$(i) \leq 2$ or count$(j) \leq 2$ ▷ Maximum two cells in row or column can be flagged
4. if any joint $i \rightarrow m$ and $j \rightarrow m$ then $i \rightarrow j$ doesn't exist. ▷ Two joints must not be connected to each other at both of their ends, else the combination represents only one link.

  if all constraints defined above are satisfied **then**
    insert node (i, j) at end of linked-list head.
  else
    update $k = k - 1$
  end if
  update $k = k + 1$
end while
Mechanism Assembly Matrix = head
▷ Link connectivity retrieval and plotting the mechanism using openGL
create new connectivity linked-list
store the first joint $(0, 1)$
store link coordinates, $(30, 0, 30, 30)$
update corresponding status to 1 in node linked-list
if $(0, j)\forall j$ **then**
  add joint $(0, j)$
  store coordinates $(70, 0, 70, 30)$
  update corresponding status to 1 in node linked-list
end if
while status != 1$\forall$ status in node linked-list **do**
  if i or j matches to previously stored values of i or j **then**
    add corresponding joint
    store coordinates by randomly generating
    update corresponding status to 1 in node linked-list
  end if
end while

two links. In such cases, the active joint will be assigned arbitrarily to any of them. The value of the active joint is computed with respect to the positive x-axis, in counter clock-wise direction.

Point of application of force: Rao 1995 [9], represents the closeness or nearness of any two links through a connectivity distance based upon the similar strategy it is assumed that the force is to be applied on the link, which is maximally separated from the base. The point of application of force will be the end point of that particular link, in case of open-end link. On the other hand, in case of a closed loop, the mid-point of that particular link will be the point of the force application. Similar to the case of active joints assignment, there is possibility that two or more links may stay at the maximum distance. In that case, point of application of force will be chosen arbitrarily.

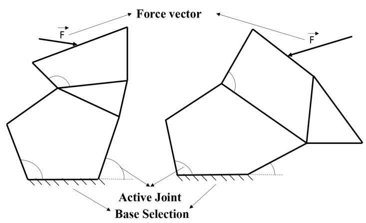


Figure 2: Selection of base, active joints, and point of application of force

5 Results and discussions

The proposed algorithm is implemented using C++ and Matlab programming. The results are obtained by varying the numbers of dof from 1 to $N-1$. On the basis of number of dof and the number of links for a specified case, the number of joints are calculated as per the Kutzbach's formulation [10]. The various mechanisms are formed for this combination of number of links and the degrees of freedom and is plotted with the help of openGL.

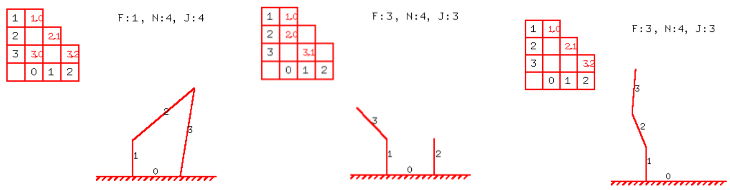
The results presented in Figs. 3(a-c) are for$N$ as 4, with F as 1 and 3. A few results are shown here out of a lot of possible results.

The Figs. 4(a-c) are for 5 number of links and numbers of dof as 2 and 4.

The resulting Figs. 5(a-c) represents the various morphologies for N as 6 and F as 1, 3 and 5.

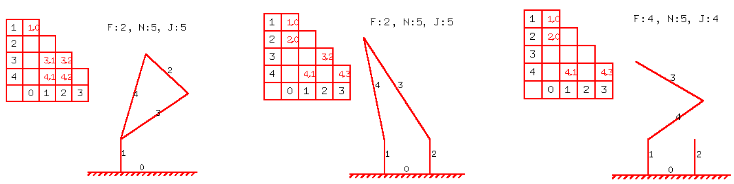
Finally, the Figs. 6(a-c) demonstrates the various morphology for N as 7 and F as 4.

From the study of these results of various mechanisms, it is observed that for any $F = N - 1$, the value J will always be equal to F. For this case, if the J number of joints are assigned diagonally - one step lower than the major diagonal - then a serial chain manipulator will be formed. For any assignment of joints in this case, there will be formation of an open chain manipulators. It may have any number of branches depending upon the assignment. Considering the case for $F = N - 3$, one close loop



(a) (b) (c)

Figure 3: N: 4, F: 1 and N: 4, F: 3



(a) (b) (c)

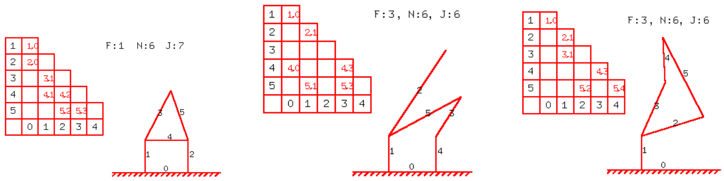
Figure 4: N: 5, F: 2 and N: 5, F: 4

will be formed in the manipulator in any type of assignment. Similarly, for $F = N - 5$, there will be formation of two closed loops in the manipulator.

Out of the results obtained for various numbers of dof and the number of links, some of the manipulators in results are quite similar to the existing well-known mechanisms. Some of the results have been selected to illustrate the selection of base, active joints and point of application of force. Since the program writing exercise for this automated selection of base, active joints and point of application of force is in progress and not a part of this paper, the proposed procedure is illustrated through the manual assignment and presented in Figs. 7(a-f).

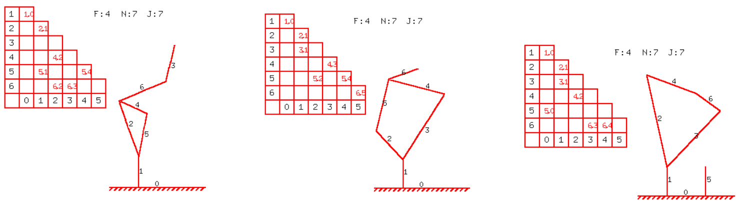
- In Fig. 7(a), the mechanism shown is a serial chain. Here, the base is shown with link number 0 from mechanism assembly matrix. All the active joints are shown starting from base. Point of application of force will be at the end of open-ended link.

- Four-bar chain mechanism is shown in Figs. 7b, c. Similar to the first case, the base is already known, represented by link 0. Now, the total number of degrees of freedom of the mechanism is 1.With two links starting from the base, the active joint can be arbitrarily assigned to any of the link. Force is to be applied at the mid of the link number 2, which is at the maximum distance from the base



(a) (b) (c)

Figure 5: N: 6, F: 1, N: 6, F: 3 and N: 6, F: 5



(a) (b) (c)

Figure 6: N: 7, F: 4

of the mechanism.

- The mechanism shown in Figs. 7(d, e) is a five-bar mechanism, where link 0 represents the base. This is mechanism has 2 degrees of freedom and both of these can be assigned to the links connected to the base. Now, links 3 and 4 are at same distance apart from the base as shown. So, the point of application of force, can be arbitrarily selected as the mid point of the link 3 or 4.

Fig. 7(f) represents a close-loop within a serial chain, in which the selection of base, active joint, point of application of force have been demonstrated.

After affixing the basic information about the base, location of active joints and point of application of force, a strategy for developing the force-torque relation for the randomly generated mechanism need to be carried out, so as to determine the Jacobian matrix of the randomly generated mechanism. Based upon the characteristics of this Jacobian, the randomly generated manipulator will be evaluated for its performance. This performance criteria will be helpful for the selection of basic morphology of hybrid manipulator out of the randomly generated morphologies using the evolutionary techniques, according to the specified task of following a trajectory or possessing a prescribed stiffness.

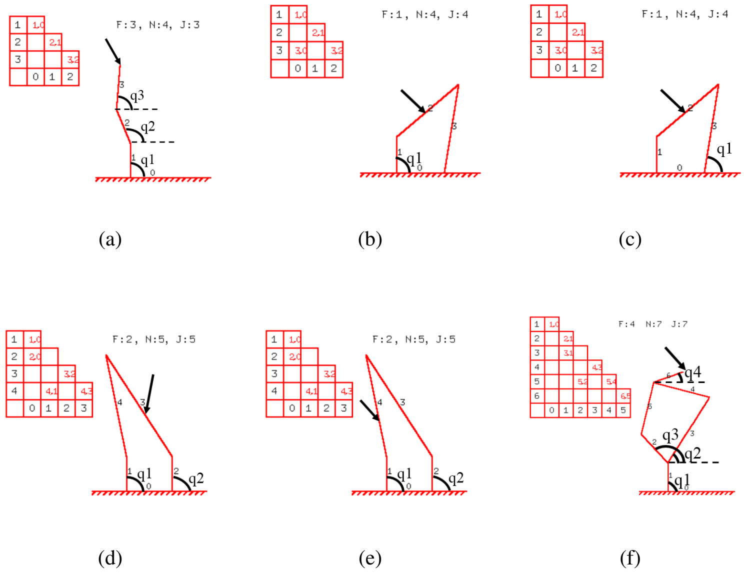


Figure 7: Angles assignment schema

6 Conclusion and future work

The work presented here finds its importance in generation and selection of basic morphologies for planar hybrid manipulators, given a stipulated number of links to be used. An algorithmic platform is developed to generate all the possible planar hybrid manipulators with a specified numbers of dof and the maximum number of links. The proposed algorithm is implemented for various numbers of dof and the results are validated with the available mechanisms. Investigations are in process for establishing a unique mapping between the randomly generated matrix elements and corresponding morphology of a hybrid manipulator. Another challenge in this direction is related to the comparative study of these randomly generated population candidates. Further work can be carried out to develop a general performance evaluation criteria of the mechanism, based on task requirement of trajectory tracking and end-effector forces.

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