A Novel Modular Strategy for the Fabrication of Robotic Manipulators Based Upon Task-Based Designs

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***Abstract*— A modular fabrication strategy for the development of customized robotic arms is proposed in this paper. With increasing variety in robotic applications, the concept of task-based customized design is expected to play a big role in deployment of robotic arms for the required jobs. Many manipulator design strategies have been presented. However, there remains a challenge of fabricating the manipulators – possessing the configurations and the parameters resulting out of the design process. This paper presents a strategy for modular development of arms. The novelty of the strategy lies in the aspect that the modules possess *adaptable* robotic parameters – to adjust the size and connecting angles of the modules according to the requirement. Given the degrees of freedom of the manipulator and the link and the joint parameters (D-H parameters in this paper), the modules are configured and assembled to develop the required manipulator. Assemblies of the modules for two standard configurations are presented in this paper to demonstrate the proposed strategy.**

Keywords— Modular, Customized, Manipulators, Task-based design

I. INTRODUCTION

A. Customized Robotic Arms

There has been a tremendous increase in the variety of robotic applications. To employ a robotic manipulator for common industrial operations, an appropriate configuration out of the available conventional manipulators is selected [1]. This selection is based upon the thorough examination of the task requirements, the working environment and the cost involved. To satisfy the needs of the robotic application, in the form of reach, dexterity, payload capacity, velocity etc., some adjustments are usually required to be made in the selected robotic arm or in the working layout. However, even minute changes in the task description may lead to significant compromises in the efficiency of the selected arm. The authors have the view that adjustment possibilities in the task-description, even after an appropriate robot is selected, would be highly appreciable. Besides, in case a robot already in use is to be utilized for any additional task, say for sharing the robot with two CNC's, possibilities of even a small alteration in the 'joint limits' and/or in the 'reach' of the robotic arm are considered admirable. This leads to the importance of *customized design* of required manipulators. In a customized design, a robotic manipulator is designed based upon the specific requirements of the application and according to the working environment.

Various researchers have presented their work on the design of task-based manipulators, considering link lengths, joint limits and/or base-point as design variables. Pioneered by the works of Kim [2], many recent publications have presented the importance of task-based designs and the corresponding challenges [3-5]. Design of a customized manipulator can be highly challenging due to complexity of the task descriptions and the constrained environment in which the task has to be performed by the manipulator. The concept of task-based manipulator design is illustrated through the situations depicted in Fig. 1. The figure shows two constrained environments for which a robotic arm is required to be designed.

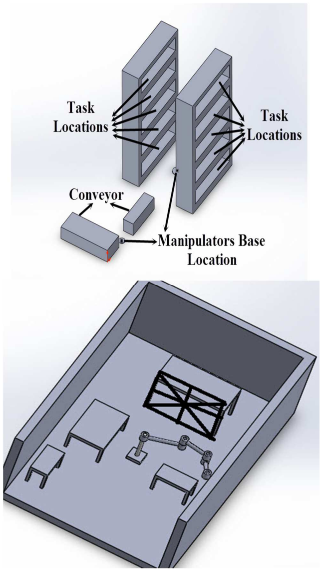

Fig. 1. Requirement of a manipulator for working inside the constrained environments

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B. Development of task-based designs: a challenging aspect

For the development of the manipulators based upon the complicated designs, the challenge lies in the lack of the correspondence between the formats of the design results and the inputs required for the fabrication units. Furthermore, the task-based design strategies are generally not dependent upon the available configurations. Hence, the complicated development planning of the desired robotic manipulator may result into some revision of the design or may take long to develop due to the missing compatibility of the given design and the fabrication processes. No significant work has been reported so far towards the assistance of the developmental processes for the robotic arms. Besides, the fabrication strategy must have some flexibility in the configuration, so as to serve the upcoming demands of the robots for increasing variety.

World's one of the leading robot manufacturing company KUKA has launched a robotic manipulator 'KR-16' in which the length of its last link can be changed. According to the change in work-environment, the reach of the manipulator can be modified. This change is done through company's professionals and is an expensive process. However, challenge lies in executing such reconfiguration with minimum expertise. To work towards the possibility of introducing modularity and reconfigurability into the development of the robotic arms, a conceptual design of the modules with adjustable D-H parameters has been proposed.

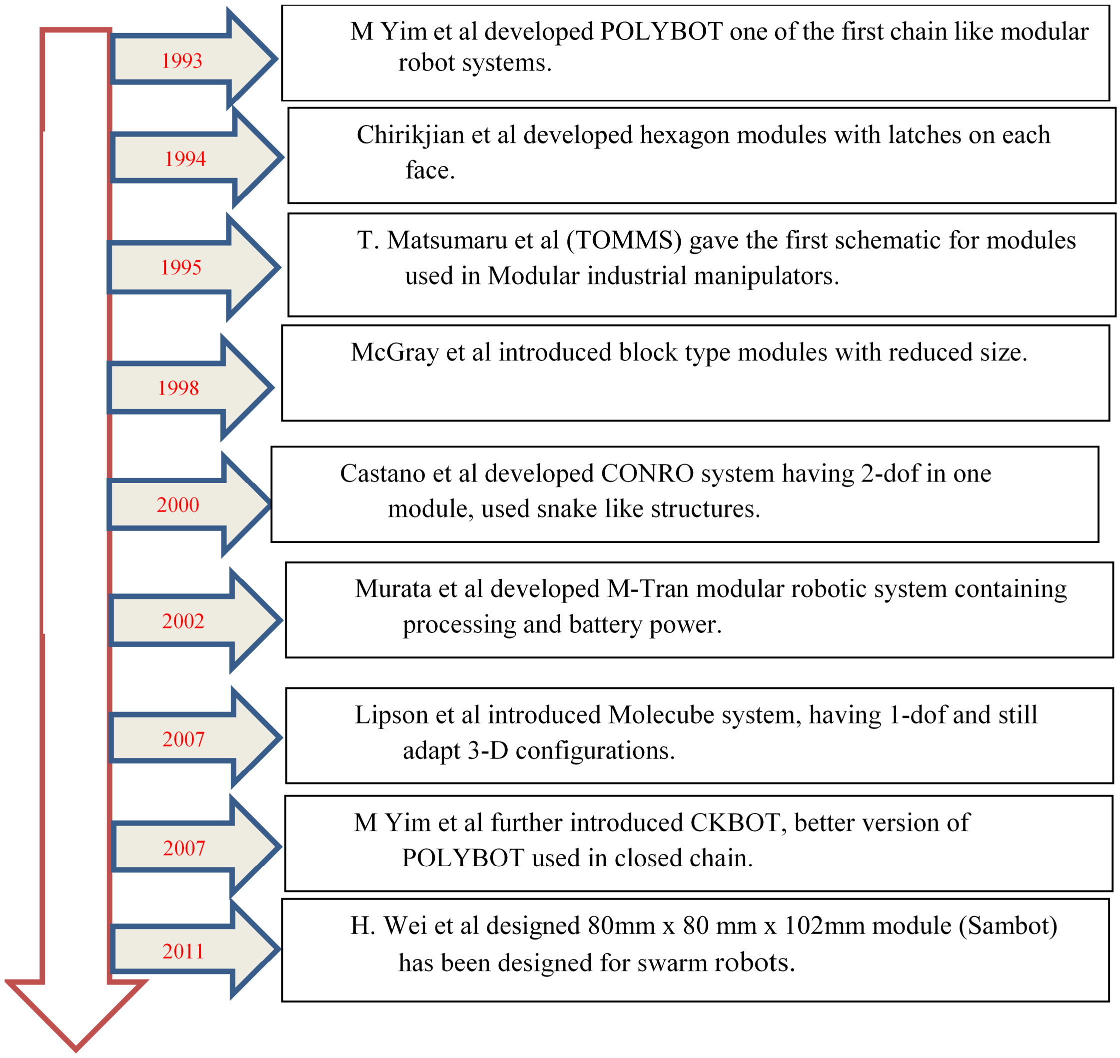

Fig. 2. Various types of modules [13 - 20]

C. Modular Reconfigurable designs – applicability in customized robotic Arms

The concept of modular reconfigurable robotic system was proposed and presented by Fukuda and Nakagawa [6]. Since then several researchers have worked upon in this direction of modular reconfigurable designs ([7-12]). Fig. 2 presents some of the contributions in this field. However, most of these tasks are for self-reconfigurable robotic systems, to be utilized for mobile manipulators. Use of modules is expected to be helpful in systematic design and in faster fabrication of manipulators for any given environment. The modular strategy can be useful both for known environments and for the situations which are not described *a priori*, *e.g.* the constrained environments resulting from natural calamities or other disastrous accidents occurring at larger level. Apart from faster assembly and installation, a modular design also possesses other desirable key features like reliability, robustness, re-usability and re-configurability. Reliability here is meant by 'availability of machine'. Availability of a machine depends upon the mean time between failures (MTBF) and mean time to repair (MTTR). Now, in a modular system, faulty module can be replaced quickly without any help from manufacturer end, which reduces MTTR. Thus, reduction in MTTR increases the availability of machine. Utilization of modular manipulators can be a boon for industrial robotic systems [22]. Towards the design and development of such modules, this paper focuses at one of the important aspects –adaptability of modules to the given link parameters.

II. Module Architecture

For a modular link to be designed in a completely general sense for all the D-H parameters as design variables – it is certainly beneficial to design generic link modules, which can adapt any real value for its link-length and twist-angle. For a given set of D-H parameters, corresponding to a design of a robotic arm which needs to be developed, the required number of modules will be adjusted according to the robotic parameters and then assembled. This modular strategy possesses many advantages. However, there arise many important questions related to the architecture of such modules, the static and dynamics of the resulting manipulators, selection of motors, controlling unit etc. This paper focuses at the first important aspect related to the module architecture.

A. Adaptable Kinematic Parameters

In a serial manipulator with *n* number of degrees of freedom, a set of *4n* D-H parameters – a_i, α_i, d_i *and* θ_i for $1 < i < n$ are used to define the kinematic structure. Out of these, *3n* parameters (a_i, α_i and d_i for $1 < i < n$) are fixed for the case of all revolute joints. In the case of any j^{th} joint being prismatic, the corresponding θ_j will be fixed and d_j will be varying. Consequently, one parameter corresponding to each joint will be varying. Change in this varying parameter provides several postures of the robotic arm. However, a change in any of the fixed parameter will change the basic configuration of the manipulator. Selection of the basic configuration, and hence the set of fixed kinematic parameters for a robotic arm, is majorly based upon the required task. Change in a task, or addition of more sub-tasks, needs to examine the workspace of the robot along with the kinematic performance of the robot in the required new postures. In such scenarios, possibility of making some certain changes in the workspace may help to great extent.

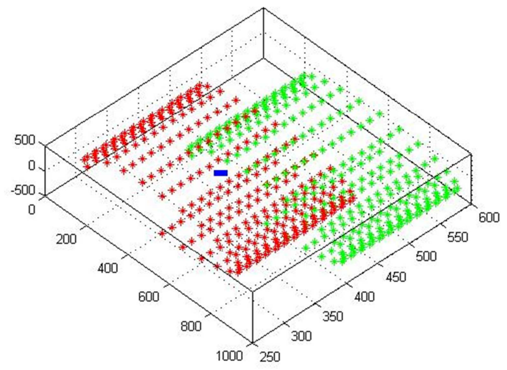

Fig. 3. Shift in the workspace with change in the D-H parameters

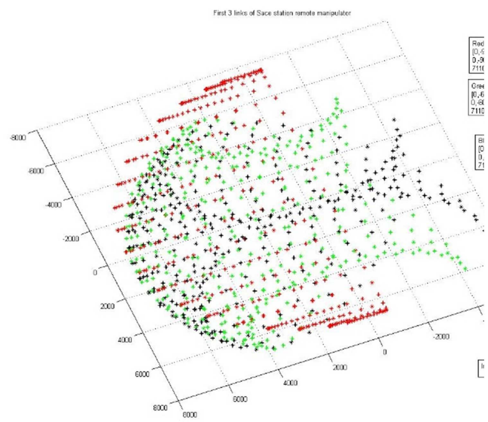

Fig. 4. Change in workspace with change in a twist angle for a 3-link manipulator

TABLE I. CHANGES IN a_0 AND IN d_1 IN A 4-LINK MANIPULATOR

i	a_{i-1}	α_{i-1}	d_i	θ_i	i	a_{i-1}	α_{i-1}	d_i	θ_i
1	**425**	90	**677**	θ_1	1	**625**	90	**877**	θ_1
2	375	0	0	θ_2	2	375	0	0	θ_2
3	0	0	d_3	0	3	0	0	d_3	0
4	0	0	200	θ_3	4	0	0	200	θ_3

Table 1 shows the D-H parameters of a robotic arm with 4 degrees of freedom (a SCARA configuration). With change in its a_0 and d_1, as highlighted in the table entries, the corresponding change (shift) in the workspace is shown in Fig. 3. Graph generated in red color shows the workspace of manipulator having lower values of a_0 and d_1. Similarly, in the second case, first three links of a space station manipulator (SSRM) has been taken under consideration. The change in the workspace is analyzed with respect to the change in α_1. Corresponding values are highlighted in Table 2 and the twists in workspace are presented in Fig. 4. The complete analysis on the effect of changes in each parameter on the workspace is not a part of this paper. This section represented the tremendous possibility of playing with the workspace, to adjust for the various tasks, in case the challenging task of modular fabrication can be worked upon.

TABLE II. CHANGES IN α_1 IN A 3-LINK MANIPULATOR

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	-90	380	θ_1
2	0	**-90**	1360	θ_2
3	7110	0	475	θ_3
i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	-90	380	θ_1
2	0	**-60**	1360	θ_2
3	7110	0	475	θ_3
i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	-90	380	θ_1
2	0	**-45**	1360	θ_2
3	7110	0	475	θ_3

In a medical surgical robot, it is important to maximize the dexterous workspace of multi-arm robots. Joint limits in surgical robots are far less than conventional ones. Value of mechanism isotropy should also be near 1 [21]. To fulfill all the objectives in the desired robot, it may be possible to get unconventional values of D-H parameters while designing. The fabrication of robotic arm with such values is a difficult task. Each operation and patient is a different set of constraints and environments, so it is difficult to attain the maximum dexterity in all the cases with good values of mechanism isotropy. Table 3 presents standard D-H parameters of a Raven IV arm, as presented in a recent work carried out by Zhi Li et al [20], on maximizing the dexterous workspace of RAVEN-IV. The work results the values of α_1 and α_2 in the range of [5, 90]. It means that the twist angles are in the range of [90,-175] and [-5,-90], respectively. To incorporate these ranges it would be beneficial to have some modular fabricating approach, so as to develop the manipulators according to the change in optimum value of twist angle.

TABLE III. STANDARD D-H PARAMETERS OF ONE OF THE RAVEN-IV ARM

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	180-α_1	0	θ_1
2	0	-α_2	0	$-\theta_2$
3	0	0	0	$90-\theta_3$
4	0	-90	d_4	0
5	0	90	0	$90-\theta_5$
6	a_5	-90	0	$90+\theta_6$

B. *Conceptual Design of a Module*

For adjustment of the link lengths, which is defined as the distance between the two consecutive joint axes '*i*' and '*i+1*' along the x-axis of the frame attached to the link '*i*', it is proposed to develop the module in two parts. The concept is illustrated through Fig. 5. Two parts are shown which can be taken as the former and the rear parts of two modules. The first part is having number of holes perpendicular to its axis and the second part is having a single hole as shown in Fig. 5 [a]. Desired length of the module can be obtained by inserting a pin in the best possible hole. Twist angle can be adjusted by a mechanism attached to parts, shown in Fig. 5 [b].

In this mechanism, a casing is provided on outer surface of second part. U-shaped rod with one end flattened can be used to attach the two parts to each other at specified twist angle. The flat end of the rod is attached to the second part, where it can rotate freely for required adjustment of the other end. The second end of the pin is threaded and can be screwed in the corresponding hole, out of the holes patterned on the outer surface of first part. The required twist-angle is thus obtained by using appropriately chosen pin-hole combination.

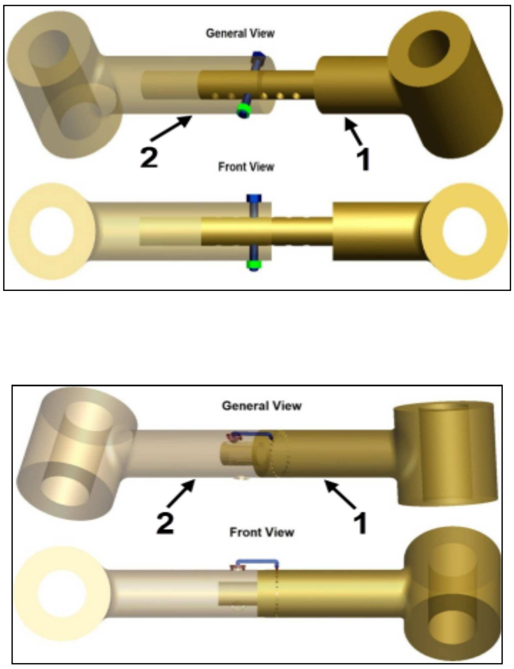

Fig. 5. Adjustment of link lengths and link twist

Now to obtain the modular configuration for different values of twist angles with limited number of holes on the first part, more number of casings can be provided on second part to hold the U-shape rod. Only one casing is to be used for single configuration. For example, if there are 24 holes, then they would be at the difference of angle of 360 ^{o}/24, i.e. 15^{o} on the circumference. Thus, using single casing, the adjustment of twist angle can be made by 15 ^{o}. The pattern of this variation can be changed by increasing the number of casings on the second part. Variation in twist angle can be further reduced by increasing the number of casings.

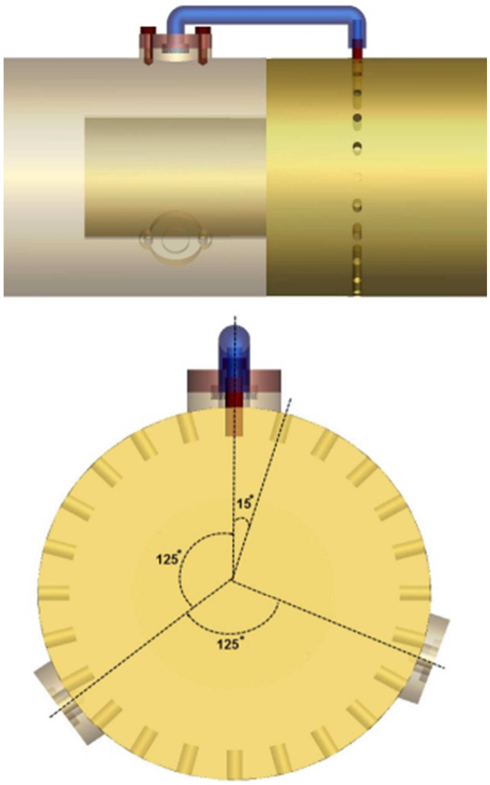

Fig. 6. Twist-angle adjustment, different views

III. Assembly – Results and Discussions

Based upon the D-H parameters of a given manipulator design, the modules can be adjusted and assembled together for the development of the robot. Robotic parameters for two standard configurations are provided in Tables 4 and 5, respectively. The results of the forward kinematics of the robotic arms, in the form of end-effector position are computed. Matlab™ has been used for the forward kinematics programming purpose.

The postures of the two manipulators, corresponding to the given joint angles, are developed using solid modeling software, Solid Works. Modules are modeled and adjusted according to the given parameters. The two assemblies representing the two cases are shown in Fig. 7 and 8, respectively. It is noted that the values calculated for the end-effector position using Matlab programming and those through the end configuration frames in the solid model are same in both the robotic arms. The results are checked for various values of twist angles and link-lengths.

TABLE IV. D-H parameters for the first three degrees of freedom of a PUMA robotic arm

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	25°
2	0	-90°	0	37°
3	205	0	10	12°
4	0	-90°	185	0°

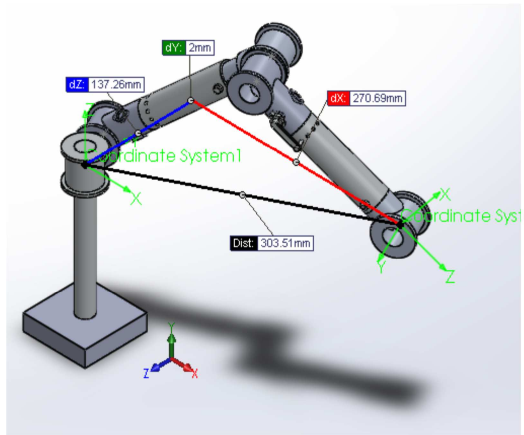

Fig. 7. Modular assembly for the first three links of PUMA configurations

In Fig. 7, the distance between the base frame, represented as coordinate frame 1 and the end-effector frame, represented as coordinate system 5, is shown. The three components in x, y and z directions are also shown which have been successfully validated. The adjustment for incorporating the values of joint offset ‘d’ have been done by adjusting the positions of the connectors of each module.

IV. Conclusion

A novel fabrication strategy for task-based robotic manipulators is proposed in this paper. The paper presents the importance of task-based customized manipulators with the increasing variety in the robotic applications. It is proposed in the paper to use the concept of modularity in the fabrication of the robotic arms, so as to adjust the unconventional values of the D-H parameters, the output of the design process. A conceptual design of the link modules is presented in the paper.

Two standard configurations are modeled using the proposed modules to illustrate the proposed strategy. The reachability results of the assembled models and the corresponding forward kinematic results have been verified successfully. The paper is an attempt to motivate the utilization of modular strategy in assisting the challenging fabrication of the design results. The concept of modularity in industrial robotic arms is expected to change the perspective of the solutions being provided to the several applications in limited resources.

TABLE V. D-H parameters for a robotic arm with SCARA configuration

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0°	0	45°
2	205	0°	40	58°
3	185	0°	-40	67°
4	185	0°	0	0°

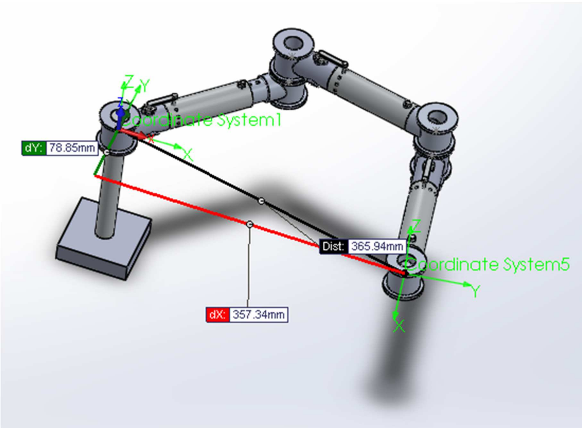

Fig. 8. Modular assembly for a SCARA configuration

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