# Development of reconfigurable serial manipulators using parameters based modules

Satwinder Singh, Atul Aggarwal, Yogesh Singhal, Ekta Singla

**Abstract**

The aim of this paper is to present a modular architecture for the design and realization of reconfigurable serial manipulators. Based on the actuator specifications – size, weight and load carrying capacity – three divisions of the modules are proposed, possessing same architectural design but different sizes. The novelty of the approach lies in the adaptability of the modules in adjusting the link lengths and the twist angles, according to a given set of design parameters. A brief description of the task-based design is included in the paper. The primary objective of this work is the architectural design of the proposed modules which can cater to the designed values of the robotic parameters. The modules are analyzed under given static load conditions. Stress analysis is performed on the components for the worst case static loading and the simulation results for one division is discussed in the work. An optimal assembly planning, including the number and the type synthesis of modules, is briefed. To demonstrate the utility of the modules in realistic work cells, design and assembly of a 6-links manipulator suitable to work in the given environment is included in the paper.

**Keywords:** Re-configurable, modular design, task-based, ssembly planning

## 1 Introduction

Modularity in a system design signifies a particular set of discrete functional components or modules, which can be assembled/re-assembled to obtain different configurations of the system. The concept of modular design of industrial robots, with each module possessing one degree-of-freedom (dof) had been proposed by Benhabib et al [1]. Many researchers have shown their interest in modular robotic arms, to gain the advantages in their maintenance — both w.r.t time involved and the inventory management. Prime advantages of the modularity are related to replacement time reduction,

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utilizing reconfigurability for several customized tasks and quik prototype development corresponding to a new design.

Modular design strategies, involving the formulation of optimization problems, had been handled in past using Genetic Algorithms and Simulated Annealing [2, 3, 4]. The concept of MDOF (Minimized Degree Of Freedom) using Evolutionary Algorithm is presented by Yang and Chen [5] for task-based design configurations. The challenges related to a modular strategy is the connectivity planning, system modelling of the reconfigured structure and the planning of the locations where a module can be fitted in. G.Acaccia [6] detailed an architectural design using three different types of joint modules - revolute, prismatic and wrist, along with the passive link modules. In some other works, the modular library mainly consists of same types of modules [5, 7], all cube-shaped and having a docking socket on each wall. No significant work is presented for the task-oriented assembly planning of the modules. Chen et. al. [8] proposed a strategy for transforming the parameters of the reconfigured manipulator into the corresponding D-H parameters and to avail the system design from the parameters information in this generalized form. However, this post-assembly practice for acquiring the system parameters is completely avoided in the present work. The new configuration is synthesized *a priori*, based on given objective(s), and the modules have been designed to adapt the resulting system parameters.

The modular architecture and the divisions are described in section 2. Section 3 presents the stress analysis of the modular units, under worst loading. Optimal assembly of the modules, including the number and the type planning, is discussed in section 4.

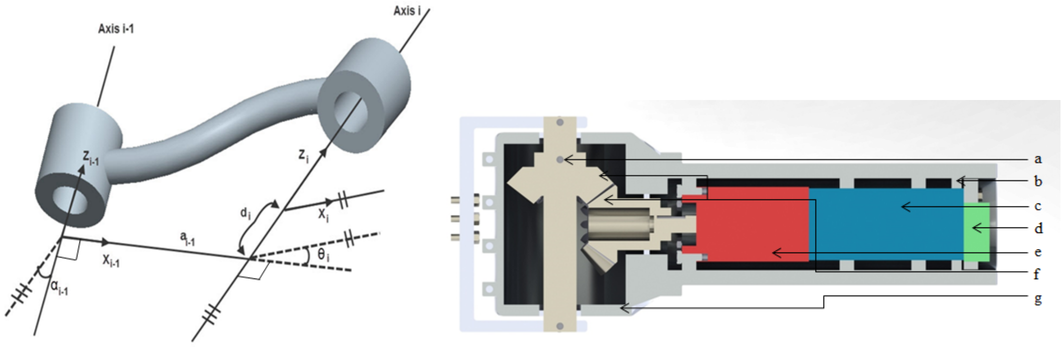
## 2 Parameters based modules: definition, architecture and divisions

A module is defined as the entity which can adapt the values of the D-H parameters, within the prescribed range, and can be connected to the other similar modules for the development of a manipulator designed for specified tasks. The DH convention is used in the current work to attach the reference frames to the links of $n$-linked manipulator (refer [9]) to define the relation between $(i-1)^{th}$ and $i^{th}$ links, $\forall\ 1 \leq i \leq n$, the four parameters – twist angle ($\alpha_{i-1}$), link length ($a_{i-1}$), joint offset ($d_i$) and joint angle $\theta_i$ are associated as shown in Fig.1(a).

The architecture of a module is planned with three units — a basic length unit, an adaptive twist unit and a length extension unit. No variation is considered in this work for offset. Fixed values of offset are used based upon the offset distance inherently present in the modular combinations.

### 2.1 Basic length unit

Basic length unit consists of a hollow cylindrical body and a gear box (shown in Fig 1(b)). The upper end is free to be attached with one of the remaining two units. The motor having encoder and reduction gear box is fitted inside the unit. The bevel gears are designed for the motion transmission in the perpendicular direction. The gear



(a) D-H parameters representation

(b) Cut section of a basic length unit (a) gear shaft (b) motor casing (c) motor (d) encoder (e) reduction gearbox (f) bevel gears (g) gear box casing

Figure 1: Parameters description and the basic length module

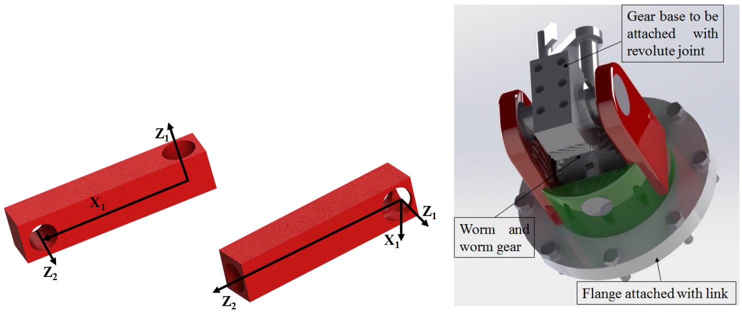
box consisting of two bevel gears, with one fixed and the other free to move. The later is attached to the motor shaft. Due to to this arrangement, power transmitted by the motor is used to rotate the hollow unit having motor itself.

## 2.2 Adaptive twist unit

This unit is used to adapt the twist angle between two successive axes of rotation, based upon the design outcome. Normally, the twist angles are designed as $90^\circ$ or $0^\circ$. However, for a large solution space, the robotic parameters are prescribed to take non-conventional values. Besides, based upon the D-H convention, a twist angle can attain same value in two different ways. For example, two axes of rotation can be at $90^\circ$ twist angle while intersecting and without intersecting, as illustrated in Fig. 2(a). These facts are taken into account for the architectural planning of this twist module. A flange, connected to the previous link, is fasten to the basic length unit (refer Fig. 2(b)). This flange is used to accommodate the twist angle change while having successive axes of rotation in parallel planes. A gear box with a worm and a half spur gear is used to adjust the successive axes of rotations, which are intersecting. Link Module is attached to the base of half spur gear. This gear mechanism is self locking and can be configured manually to adapt the corresponding design outcome of the twist angle. Hence, using this module, twist angle can be adjusted and reconfigured according to the design.

## 2.3 Extended length module

Extended length component is the attachment for enhancing the basic lengths. The limit of extension is different for each division of modules, based upon the length limits which can be accommodated within the corresponding maximum allowable torques. Two flanges are present at both ends of the unit and can be fasten to the other units



(a) The successive joint axes states - parallel-perpendicular and intersecting-perpendicular

(b) Adaptive twist unit

Figure 2: Architectural planning of a twist module

using bolts.

## 2.4 Module divisions

The proposed modules have 3 divisions based on their size, represented as $H$, $M$ and $L$. Architectural layout is kept same for all the divisions. Variation in size is due to the three different motors used to actuate the joints. Weight carrying capacity of each link is an important aspect in open chain structure. Each link needs to bear the weights of the links and actuated joints attached after it. Motor-gear assemblies have their own weights and torque capacities. The location of a module in the serial chain plays the important most role, and this aspect is handled in this work through the selection of three divisions. The compromise in the number of divisions is a *trade-off* between the less variation required for ‘modular’ construction, and more variety preferable for the different locations of the modules for a large number of dof manipulator.

A generalized selection criteria for the number of divisions is proposed.

1. Decide on a maximum number of dof $n_{max}$, with $n_m$ denoting the manipulator degrees and the $n_e$ denoting the dof for the orientation of the end-effector. Select the value for the maximum payload capacity, as $\mathcal{P}$.

2. Give average values of the D-H parameters, based upon their limits. Let the link lengths attain maximum value for the approximate worst torque conditions. $L_m$ and $L_e$ denote the lengths decided for the manipulator links and the far end orientation links.

3. Prepare a database of the motors-gear assemblies, from which the motors need to be selected. One such list with eight number of motors is shown in Fig 3.

4. Based upon the *worst torques* [1] resulting for each joint, three different motor-

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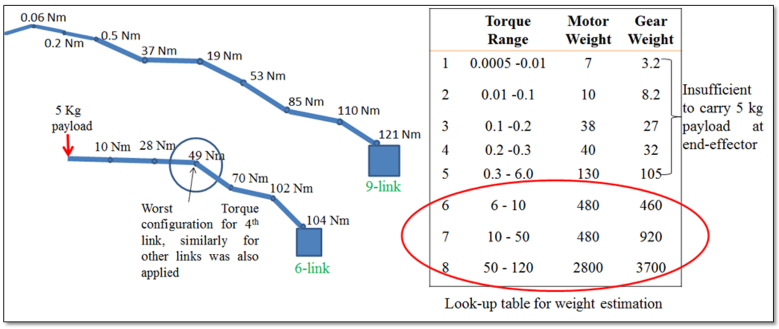
[1] Worst torque is the maximum torque required at a joint within the complete workspace of a manipulator. It is computed through an optimization problem formulation for each link, within the limits of all the joints. Worst joint is different for each joint.

gear assemblies will be selected.

The procedure is executed for various cases, keeping several values for the above parameters. Two cases are shown in Fig. 3. These correspond to the input as $[n_{max} = 9$, $n_m = 6$, $L_m = 200$, $n_e = 3$, $L_e = 50$, $\mathcal{P} = 0.5]$ and $[n_{max} = 6, n_m = 0, L_m = 200, L_e = 0, \mathcal{P} = 5]$. The three motors which have been marked in the figure are selected to cater the requirements for design and development of modules. The maximum torque capacity of the motors, geometrical sizes and weights are included in the design of the three divisions of modules, to be represented as Heavy (H), Medium (M) and Light (L).



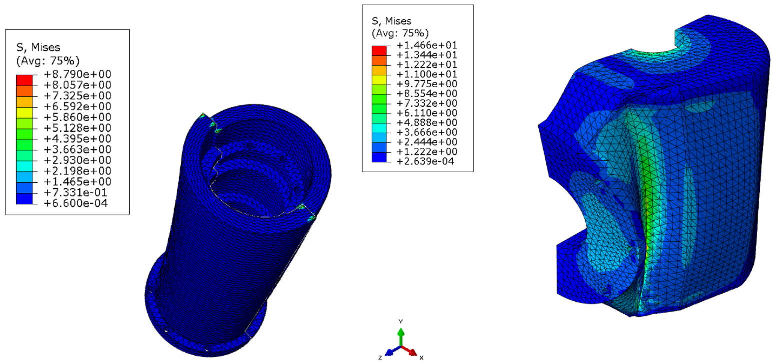
| | Torque Range | Motor Weight | Gear Weight |
|---|---|---|---|
| 1 | 0.0005 -0.01 | 7 | 3.2 |
| 2 | 0.01 -0.1 | 10 | 8.2 |
| 3 | 0.1 -0.2 | 38 | 27 |
| 4 | 0.2 -0.3 | 40 | 32 |
| 5 | 0.3 - 6.0 | 130 | 105 |
| 6 | 6 - 10 | 480 | 460 |
| 7 | 10 - 50 | 480 | 920 |
| 8 | 50 - 120 | 2800 | 3700 |

Look-up table for weight estimation

Figure 3: Motor selection process: joint torques of both the case studies, a look table for motor selection and torque range of each motor

# 3 Structural analysis

In this section, FEM analysis of primary parts of a heavy module is presented. The proposed payload at the end-effector and the cumulative weight of the maximum number of modules, which can be added in a serial chain is taken as maximum load for analysis of the above parts. This load which turns out to be 25 $kg$ with 3.5 $kg$ tolerance is computed at worst possible configurations. Similarly other modules and their respective parts were also analyzed. Both the components are made up of Aluminium-6061-T4 Alloy. Ultimate tensile Stress and yield strength of the material are 207 Mpa and 110 Mpa respectively. Hence its shown in Fig. 4(a) and 4(b) that maximum stress value produced in the above cases are far below the failure stress value. The gears used the modules are made up of AISI-8620 case hardened steel. The maximum stress produced in bevel gear (revolute joint) and spur gear (twist unit) are 198.5 Mpa and 136.2 Mpa respectively. The value of ultimate tensile stress of the material is 600 Mpa which is far above from the maximum stress produced in the components.



(a) Cylinder Casing: Maximum Stress = 8.8 Mpa (b) Gear Casing: Maximum Stress = 14.66 Mpa

Figure 4: Stress analysis of the components

# 4 Optimal modular assembly planning

For the development of a modular robot from the proposed types of modular library, the number of modules, selection of their types and the planning of their connectivity is presented.

## 4.1 Number synthesis

The minimum number of dof is determined in the first phase, along with a feasible design solution for reachability at all the TSLs in a working environment. A *nested optimization problem* is formulated and *binary search method* is applied at the outer layer to solve the unidirectional search for the number of dof. In the inner loop, problem achieves the objective of reachability for all the TSLs avoiding all the environmental constraints for each outer loop candidate.

## 4.2 Type synthesis

After affixing the minimum number of dof $n$, next is to define all possible combinations of modules and to select an optimal combination out of these assemblies. For the collection of all the possible combinations, assembly rules have been developed.

1. Fix Link-1 : $H$, Link-$n$ : $L$.
2. Connect $H \rightarrow H$ or $H \rightarrow M$
3. Connect $M \rightarrow M$ or $M \rightarrow L$
4. Connect $L \rightarrow L$
5. Maximum number similar module divisions used in one assembly are 3, 4 and 5 for $H$, $M$ and $L$, respectively.

Out of the total number of possible assembly combinations for $n$ dof, an optimal modular assembly is selected while minimizing the sum of the *worst joint torques* over the joint variables as

$$\mathcal{G}_{i_{max}} = \max_{\theta} \quad {n_i}^T z_i \qquad \forall\, i = 1, 2, \cdots, n; \tag{1}$$

where, the torques and the forces of interaction are computed through recursive inward equations, from link-$n$ to link-1,

$$\begin{aligned} n_i &= R^i_{i+1} n_{i+1} + P_{c_i} \times F_i + P_{i+1} \times R^i_{i+1} f_{i+1} + N_i; && (2)\\ f_i &= R^i_{i+1} f_{i+1} + F_i. && (3)\end{aligned}$$

$R^i_{i+1}$ represents the kinematics of the adjacent links, $F_i$ and $N_i$ are inertial force and torque acting at the center of mass of link-$i$. There will be $n$ number of inner loop executions to compute the objective function for the outer loop, as

$$\mathcal{F} = \mathcal{G}_{1_{max}} + \mathcal{G}_{2_{max}} + \cdots + \mathcal{G}_{n_{max}}; \tag{4}$$

The outer loop is formulated for minimizing $\mathcal{F}$ over $\mathbf{x}$ — the set of design variables, i.e. the robotic parameters. Optimal function value and the corresponding design parameters are computed for each assembly combination. The assembly with least value of the objective function is selected for the development of the modular manipulator for the given task.

# 5 Results and discussions

## 5.1 Connectivity illustration: modular assembly of RAVEN-II reconfiguration

A medical robot, RAVEN-II, customized for surgery possesses non-conventional twist angle values. The proposed modular architecture is able to connect at these unusual customized configurations, for the parameters given as shown in Fig.5.

## 5.2 Case study: Server room environment

The proposed methodology is implemented for a cluttered environment of a server room. A modular robot is expected to provide a solution for the cleaning and temperature sensing services at the intricate locations of different arrangement of server rooms. Task space locations (TSLs) of one such workspace are $(40, 17.3, 13.5)$, $(30, 23.4, 21.2)$ and $(20, 26.9, 3.3)$. A 6 dof manipulator is resulted out of the first phase of number synthesis. The type synthesis results into 7 possible assembly combinations. Fig.6(a) shows the environment and the postures of the 6-link manipulator with the feasible parameters, for reaching the TSLs. An optimal assembly is selected which possesess minimum sum of normalized torques as shown in Fig. 6(b). The corresponding modular assembly is shown in Fig.6(c).

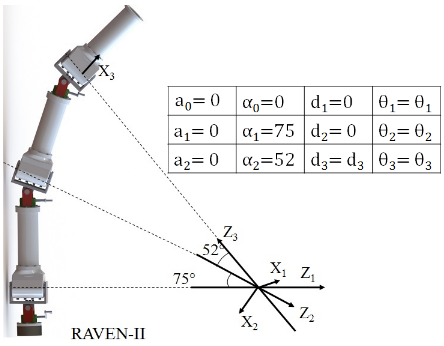
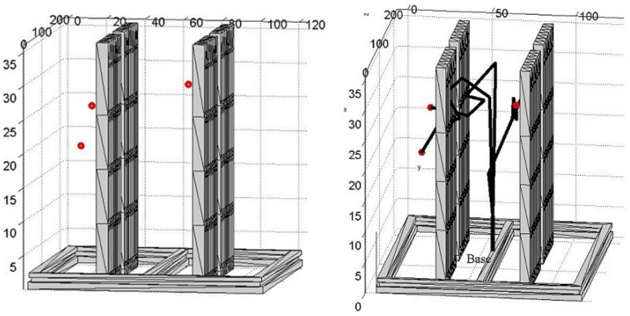
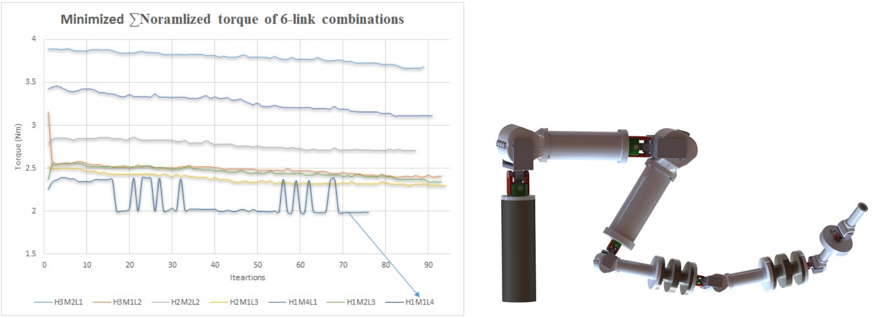


Figure 5: Medical surgical manipulator RAVEN-II developed using modules.



(a) A 6-dof manipulator design in server room environment



(b) Comparison of all possible 6-link assembly combinations.

(c) Optimal assembly $H1M1L4$.

Figure 6: Case Study: A Server Room Environment

# 6 Conclusion

Parameters based modular architecture and corresponding assembly planning is presented for reconfigurable robotic manipulators. The correspondence of the adaptable modules with the optimal design procedures is the main contribution of the paper. The modules library consists of three divisions with similar architecture. Basic length units, adaptable twist unit and extended length unit collectively form one module of the type $H$, $M$ and $L$ size. The advantage of the work is the elimination of any recalibration required after the reconfiguration of the manipulator, since the robot design is determined *a priori*. A modular assembly corresponding to RAVEN-II configuration is included in the paper for illustration. A case study on the design and modular assembly of a manipulator for a realistic server room environment is .

# Acknowledgement

Authors gratefully acknowledge the financial support of Department of Science and Technology (DST), Govt. of India, for this work.

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