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Design of Reconfigurable Joints for the Advance Robotic Systems

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Abstract

Hard (Machinery Systems) and logical (Software and Controls) modularity principles are currently used to achieve the required configurations to overcome any unexpected tasks or to meet rapid changes in production. The goal here is to ensure that the hard and logical enablers have a self-reconfiguration capability to accommodate any demanded variations. The proposed self-reconfigurable system development will identify as many robotic systems and controls as possible, which will provide all needed configurations to cope with many different applications. The significance of the reconfigurable modeling approach is that it can be used for the space, medical and industrial applications. The kinematic comparison between different robotic systems used in space, medicine and industry has been done. All these robots are kinematically similar and the most important common property is that all of them have fixed kinematic structure. An important element of the future reconfigurable robots is reconfigurable joints, which can sustain all predicted kinematic machine configurations. The goal of this research is to design desk-top proof-of-concept demo reconfigurable joints. Based on the previously proved reconfigurable modeling theory, different joint kinematic configurations will be selected and unified in a single joint model. The construction of a reconfigurable joint includes design of a gear box or clutch that can support the joint reconfigurations. This novel joint will have only one motor. The possible joint reconfigurations can be: changing positive direction of joint rotation and/or translation, changing type of joint motion such as rotational to translational and vice versa, etc. This methodology is applied to the SCARA robot manipulator to improve its last joint capability. The last joint four is replaced with new reconfigurable joint and robot kinematic theory is applied for model evaluation.

Keywords: Reconfigurable, Joints, Robots, SCARA

1. Introduction:

The manufacturing industry depends on the market change, technology and society[1]. If companies can react to the rapid changes of the market, they can survive[1]. Adjusting the product in a prompt manner is a fundamental concept that would make this change happens. This leads to the definition of Reconfiguration, which means the upgrading of the system to function beyond the capacity of the original form. Reconfiguration will not be beneficial if the new and the old technologies can’t be promptly integrated[2]. What is really needed in today’s rapid market change is the capacity to adjust the production to the rapid change in product demand[12]. Responding to the change in the industry and being cost effective are essential to a successful reconfiguration success[12]. Reconfigurable modules have been subjected to researches, in extreme environments[1], where there is a big necessity for tools that can perform different tasks in the inner and outer space[3]. In certain conditions, the reconfigurable modules should be able to fit in a very limited pace[3]. The elimination of the need to implement more hardware is a factor that should be taken in consideration. This would prevent accommodating the old system to complicated calculations for new parameters related to the weight, volume and power consumption. Changing the shape of reconfigurable modules was investigated in many researches[1,3,5,6,7,10,11], showing how this technology has used the biological system as a base for design and reconfiguration. This system is an example of how the flexibility of the response to change is intelligent, and can prevent a big loss in case that it didn't exist[6,7,9,10]. On the other hand, there are many researches that are related to the reconfiguration of joints, replacing the rigidity with flexibility, and increasing the degree of freedom. Modular and reconfigurable robots (MRRs) were investigated[4,14,15]. Some complex environments can be accessed only by modular self reconfigurable robots[4]. Encouraging researches in MRR over the common programmable expensive robots were supported in a comparison between the two generations, emphasizing the limitation imposed by the hardware constraints[14]. Some Task-based Configuration Optimization (TBCO) algorithms have been developed to find the most suitable Kinematic Configuration[15]. However, as this paper presents the reconfiguration of some programmable robots are still easily achievable despite of these limitations.

The necessity of docking system was pointed out in the original reconfiguration joint[1]. This way, the autonomous modules can change their shapes, and the number of links, and change their nature from closed, or open chains to single or multiple ones.

1.1 Denavit and Hartenberg representation:

Single closed chain is a mechanism formed from a sequence of rigid objects coupled end to end[5]. D-H representation is a convention presented by Danavit and Hartenberg in 1955 to represent the parameters of the functioning machining robot[5].

1.2 SCARA robot:

SCARA stands for Selective Compliance Assembly Robot Arm[13]. It provides motions with 4 degrees of freedom (DOF) [13]. It usually consists of three rotational joints and one transitional joint. The transitional joint is either near the base frame, or near the end-effector[13].

The SCARA robot would apply the end-effector against the surface that constitutes the workspace. This surface could be harmed if high pressure is applied. By adding a double joint to the reconfigurable joints presented in this paper, the damage can be avoided.

Figure1 represents original SCARA robot frames with their respective link lengths. D-H parameters of the SCARA robot are shown in the Table1.

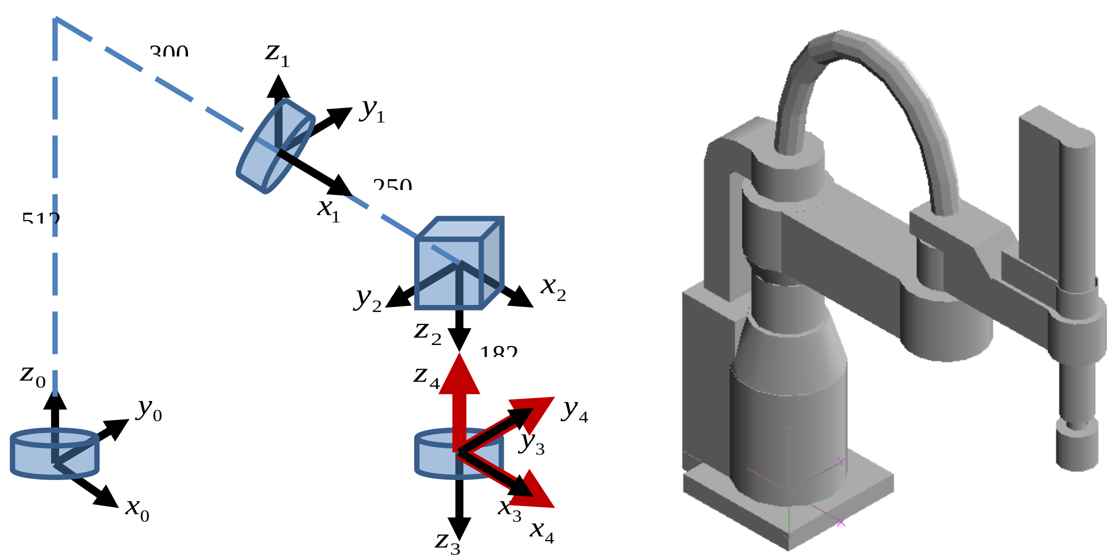


Figure 1: SCARA robot (4DOF) with original frames

Table1: D-H parameters for SCARA robot

i	d_i	θ_i	a_i	α_i
1	512	0	300	0
2	0	0	250	180
3	182	0	0	0
4	0	0	0	180

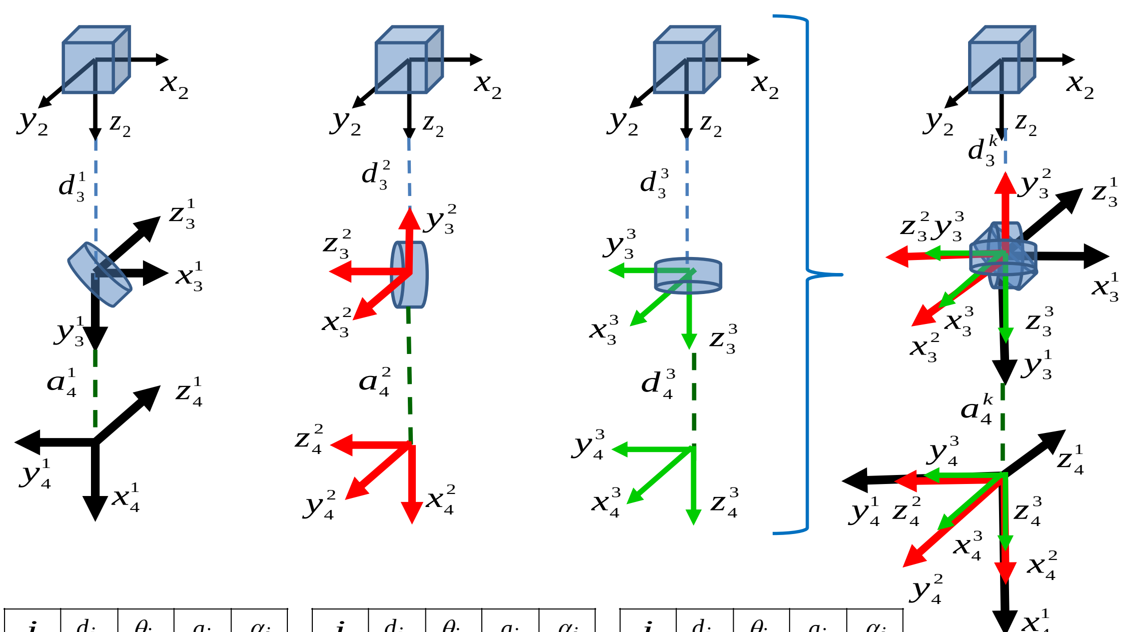
2. The Development of Reconfigurable Joint:

This research presents a novel methodology for modeling highly reconfigurable robot joints, as an essential part of the future robotic systems.

In this paper, docking system can be replaced by the constraint applied by the treated surface. Based on this constraint the D-H parameters are changed to meet the new joint rotation. In this case sensor's role is played by the degree of joint's flexibility by evaluating the force applied on the end-effector. When this force reaches the threshold defined be the joint's flexibility, this joint can rotate accordingly. The original robot with 4DOF is reconfigured to a Special Application Robot of $(3+k)DOF$, where k is one of the three possible joint configurations that are unified into one joint. This paper presents the reconfigured robot model and the calculation.

Three rotational joints were added to the original robot to achieve the goal, an application that could be mostly related to cleaning surface.

The newly designed Reconfigurable joint Frames are represented in the Figure 2, and the unification of all frames can be seen here. Their D-H parameters are presented in the table below.



i	d_i	θ_i	a_i	α_i
3	d_3^1	0°	0	90°
4	0	90°	a_4^1	0°

i	d_i	θ_i	a_i	α_i
3	d_3^2	90°	0	-90°
4	0	-90°	a_4^2	0°

i	d_i	θ_i	a_i	α_i
3	d_3^3	90°	0	0°
4	d_4^3	0°	0	0°

Figure 2: Reconfigurable joint frame structure

The reconfigurable joint in this study was initially designed with a single end effector, but according to the D-H parameters, different end effectors frames were used.

The Figure 3 represents a SCARA robot and the new reconfigurable joint frames together. The D-H parameters for the model are presented in the table2. They are varying according to the Kinematic structure of the new joint.

Although our new designed robot theoretically has **6**DOF, the state of the reconfigured joint is selected out of three cases; each case's joint will be individually the successor of the joint 2. It shall be mentioned that the new robot is using the same number of motors as before. There was no addition of any new motor. The motor that was functioning the old end-effector is now functioning the whole reconfigurable combination including the new end-effector. D-H reconfigurable parameters are presented in equations (1) and (2).

$$K_{Si} = \sin(\pm 90^\circ) = \pm 1 \quad (1)$$

$$K_{Ci} = \cos(\pm 180^\circ;0) = \pm 1 \quad (2)$$

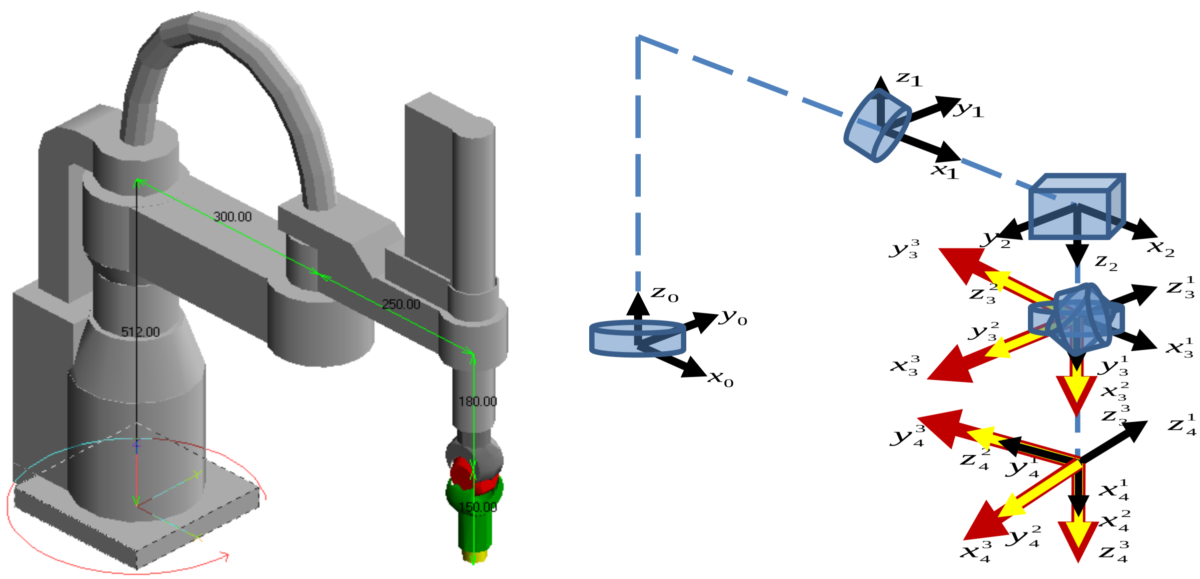


Figure 3: SCARA Robot with New Reconfigurable joint (4DOF)

Table 2: D-H parameters for 4 DOF Reconfigurable robot

i	d_i	θ_i	a_i	α_i	Reconfigurable parameters
1	d_{DH1}	$^*\theta_1 = 0^\circ$	a_1	0°	$K_{C1} = 1$
2	d_{DH2}	$^*\theta_2 = 0^\circ$	a_2	180°	$K_{C2} = -1$
$^k 3$	$^*d_3^k$	$\theta_{DH3}^k = 0^\circ \, or \, 90^\circ$	0	$0^\circ, \pm 90^\circ$	$K_{S3} + K_{C3}$
$^k 4$	d_{DH4}^k	$^*\theta_{DH4}^k = 0^\circ \, or \pm 90^\circ$	a_4^k	0°	$K_{C4} = 1$

The homogeneous transformation matrix for the n-DOF Global Kinematic Model (n-GKM) is shown in equation[1] (3).

$$ {}^{i-1}A_i = \begin{bmatrix} \cos(R_i\theta_i + T_i\theta_{DHi}) & -K_{Ci}\sin(R_i\theta_i + T_i\theta_{DHi}) & K_{Si}\sin(R_i\theta_i + T_i\theta_{DHi}) & a_i\cos(R_i\theta_i + T_i\theta_{DHi}) \\ \sin(R_i\theta_i + T_i\theta_{DHi}) & K_{Ci}\cos(R_i\theta_i + T_i\theta_{DHi}) & -K_{Si}\cos(R_i\theta_i + T_i\theta_{DHi}) & a_i\sin(R_i\theta_i + T_i\theta_{DHi}) \\ 0 & K_{Si} & K_{Ci} & R_i d_{DHi} + T_i d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) $$

Joint1 is rotational: $R_1 = 1$ and $T_1 = 0$, $K_{C1} = 1$, $K_{S1} = 0$
Joint2 is rotational: $R_2 = 1$ and $T_2 = 0$, $K_{C2} = -1$, $K_{S2} = 0$
Joint3 is translational: $R_3 = 0$ and $T_3 = 1$, $K_{S3} + K_{C3}$
Joint 4 is reconfigurable rotational: $R_4 = 1$ and $T_4 = 0$, $K_{C4} = 1$, $K_{S4} = 0$
The homogeneous transformation matrix for the Link1, Link2 shown in equation 4 and 5 is:

$$ {}^{0}A_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & a_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & a_1\sin\theta_1 \\ 0 & 0 & 1 & d_{DH1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4) $$

$$ {}^{1}A_2 = \begin{bmatrix} \cos\theta_2 & \sin\theta_2 & 0 & a_2\cos\theta_2 \\ \sin\theta_2 & -\cos\theta_2 & 0 & a_2\sin\theta_2 \\ 0 & 0 & -1 & d_{DH2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5) $$

The homogeneous transformation matrix for the Link 3 (Reconfigurable joint) is shown in the equation (6). The joint has six different configurations.

$$ {}^{2}A_{3k} = \begin{bmatrix} \cos\theta_{DH3}^{k} & -K_{C3}\sin\theta_{DH3}^{k} & K_{S3}\sin\theta_{DH3}^{k} & 0 \\ \sin\theta_{DH3}^{k} & K_{C3}\cos\theta_{DH3}^{k} & -K_{S3}\cos\theta_{DH3}^{k} & 0 \\ 0 & K_{S3} & K_{C3} & {}^{*}d_3^{k} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6) $$

The homogeneous transformation matrix for the Link 4 (End effector) shown in equation 7.In this case end effector has three different configurations.

$$ {}^{3k}A_{4k} = \begin{bmatrix} \cos\theta_4^{k} & -\sin\theta_4^{k} & 0 & a_4^{k}\cos\theta_4^{k} \\ \sin\theta_4^{k} & \cos\theta_4^{k} & 0 & a_4^{k}\sin\theta_4^{k} \\ 0 & 0 & 1 & d_{DH4}^{k} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7) $$

3. Reconfigurable robot forward kinematics

To calculate forward kinematics for the reconfigurable joint, we need to multiply ${}^{0}A_1$ by ${}^{1}A_2$ by ${}^{3}A_{3k}$ by ${}^{3k}A_{4k}$. This calculation is given with the equations (8) and (9).

$$ {}^{0}A_{4k} = {}^{0}A_{1}\,{}^{2}A_{2}\,{}^{3}A_{3k}\,{}^{3k}A_{4k} \quad (8) $$

$$ {}^{0}A_{4k} = \begin{bmatrix} n_{xk} & b_{xk} & t_{xk} & p_{xk} \\ n_{yk} & b_{yk} & t_{yk} & p_{yk} \\ n_{zk} & b_{zk} & t_{zk} & p_{zk} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9) $$

Where k is one out of three cases as it is mentioned earlier.
Maple 17 was used to multiply these different matrices, in order to get the unified forward kinematics equations. The formulas were simplified with the excluded case of K_{C3} is zero just for simplicity. See equations (10)-(18).

$$ n_x = A_{04k}[1,1] = \cos(\theta_1 + \theta_2 - \theta_{DH3k} - K_{C3}\theta_{DH4k}) \quad (10) $$
$$ n_y = A_{04k}[2,1] = \sin(\theta_{DH3k} + K_{C3}\theta_{DH4k}) \quad (11) $$
$$ n_z = A_{04k}[3,1] = -k_{S3}\sin(\theta_{DH4k}) \quad (12) $$
$$ s_x = A_{04k}[1,2] = -\sin(\theta_1 + \theta_2 \mp (\theta_{DH3k} + K_{C3}\theta_{DH4k})) \quad (13) $$
$$ s_y = A_{04k}[2,2] = -\cos(\theta_1 + \theta_2 \mp (\theta_{DH3k} + K_{C3}\theta_{DH4k})) \quad (14) $$
$$ s_z = A_{04k}[3,2] = -k_{S3}\cos(\theta_{DH4k}) \quad (15) $$
$$ a_x = A_{04k}[1,3] = -k_{S3}\sin(\theta_1 + \theta_2 - \theta_{DH3k}) \quad (16) $$
$$ a_y = A_{04k}[2,3] = k_{S3}\cos(\theta_1 + \theta_2 - \theta_{DH3k}) \quad (17) $$
$$ a_z = A_{04k}[3,3] = -K_{C3} \quad (18) $$

3.1 Special Cases

The cases that should be looked at are some selections among the three chosen frames' states, the variable here are θ_{DH3k}, K_{C3}, and k_{S3}. Where, in all cases, d_{3k} is 180, and d_{DH4k} is 150, and θ_{DH3k} would take three different values: $\theta_{DH31} = 0^\circ$, $\theta_{DH31} = 90^\circ$, and $\theta_{DH31} = -90^\circ$, as it is shown in Table 2.

3.1.1 first case:

$\theta_3 = 0, k_{C3} = 0, k_{S3} = 1$. See equations (19) to (30).

$$ n_x = A_{04k}[1,1] = \cos(\theta_1 + \theta_2 - \theta_{DH4k}) \quad (19) $$
$$ n_y = A_{04k}[2,1] = \sin(\theta_1 + \theta_2 - \theta_{DH4k}) \quad (20) $$
$$ n_z = A_{04k}[3,1] = -\sin(\theta_{DH4k}) \quad (21) $$
$$ s_x = A_{04k}[1,2] = 0 \quad (22) $$
$$ s_y = A_{04k}[2,2] = 0 \quad (23) $$
$$ s_z = A_{04k}[3,2] = -\cos(\theta_{DH4k}) \quad (24) $$
$$ a_x = A_{04k}[1,3] = -\sin(\theta_1 + \theta_2 - \theta_{DH4k}) \quad (25) $$
$$ a_y = A_{04k}[2,3] = \cos(\theta_1 + \theta_2 - \theta_{DH4k}) \quad (26) $$
$$ a_z = A_{04k}[3,3] = 0 \quad (27) $$
$$ p_x = A_{04k}[1,4] = a_{4k}\cos(\theta_1 + \theta_2) - d_{DH4k}\sin(\theta_1 + \theta_2) + a_2\cos(\theta_1 + \theta_2) + a_1\cos(\theta_1) \quad (28) $$

$$p_y = A_{04k}[2,4] = a_{4k}\sin(\theta_1+\theta_2) + d_{DH4k}\cos(\theta_1+\theta_2) + a_2\cos(\theta_1+\theta_2) + a_1\sin(\theta_1) \quad (29)$$
$$p_z = A_{04k}[3,4] = -d_{3k} + d_{DH2} + d_{DH1} \quad (30)$$

3.1.2 second case:

$\theta_3 = \pi/2, k_{C3} = 0, k_{S3} = -1$. See equations (31) to (42).

$$n_x = A_{04k}[1,1] = \sin(\theta_1+\theta_2-\theta_{DH4k}) \quad (31)$$
$$n_y = A_{04k}[2,1] = -\cos(\theta_1+\theta_2-\theta_{DH4k}) \quad (32)$$
$$n_z = A_{04k}[3,1] = \sin(\theta_{DH4k}) \quad (33)$$
$$s_x = A_{04k}[1,2] = 0 \quad (34)$$
$$s_y = A_{04k}[2,2] = 0 \quad (35)$$
$$s_z = A_{04k}[3,2] = \cos(\theta_{DH4k}) \quad (36)$$
$$a_x = A_{04k}[1,3] = -\cos(\theta_1+\theta_2-\theta_{DH4k}) \quad (37)$$
$$a_y = A_{04k}[2,3] = -\sin(\theta_1+\theta_2-\theta_{DH4k}) \quad (38)$$
$$a_z = A_{04k}[3,3] = 0 \quad (39)$$
$$p_x = A_{04k}[1,4] = -d_{DH4k}\cos(\theta_1+\theta_2) + (a_{4k})\sin(\theta_1+\theta_2) + a_2\cos(\theta_1+\theta_2) + a_1\cos(\theta_1) \quad (40)$$
$$p_y = A_{04k}[2,4] = -d_{DH4k}\sin(\theta_1+\theta_2) - a_{4k}\cos(\theta_1+\theta_2) + a_2\cos(\theta_1+\theta_2) + a_1\sin(\theta_1) \quad (41)$$
$$p_z = A_{04k}[3,4] = a_{4k}\sin(\theta_{DH4k}) - d_{3k} + d_{DH2} + d_{DH1} \quad (42)$$

3.1.3 third case:

$\theta_3 = -\pi/2, k_{C3} = 1, k_{S3} = 0$. See equations (43) to (54).

$$n_x = A_{04k}[1,1] = \sin(\theta_1+\theta_2-\theta_{DH4k}) \quad (43)$$
$$n_y = A_{04k}[2,1] = -\cos(\theta_1+\theta_2-\theta_{DH4k}) \quad (44)$$
$$n_z = A_{04k}[3,1] = 0 \quad (45)$$
$$s_x = A_{04k}[1,2] = -\cos(\theta_1+\theta_2-\theta_{DH4k}) \quad (46)$$
$$s_y = A_{04k}[2,2] = -\sin(\theta_1+\theta_2-\theta_{DH4k}) \quad (47)$$
$$s_z = A_{04k}[3,2] = 0 \quad (48)$$
$$a_x = A_{04k}[1,3] = 0 \quad (49)$$
$$a_y = A_{04k}[2,3] = 0 \quad (50)$$
$$a_z = A_{04k}[3,3] = -1 \quad (51)$$
$$p_x = A_{04k}[1,4] = -a_{4k}\sin(\theta_1+\theta_2-\theta_{DH4k})\sin(\theta_{DH4k}) + a_2\cos(\theta_1+\theta_2) + a_1\cos(\theta_1) \quad (52)$$
$$p_y = A_{04k}[2,4] = -a_{4k}\cos(\theta_1+\theta-\theta_{DH4k}) + a_2\cos(\theta_1+\theta_2) + a_1\cos(\theta_1) \quad (53)$$
$$p_z = A_{04k}[3,4] = -d_{DH4k} - d_{3k} + d_{DH2} + d_{DH1} \quad (54)$$

4. Conclusion:

As we have discussed throughout the paper, we have successfully reconfigured a SCARA robot from being limited to 4-DOF to a 6-DOF. There are three combinations in the reconfigured joint, but the state of the joint has to be selected by the motion of the end-effector, and the constraint applied by the treated surface. Unlike the complicated mathematics explained in this study, the design will be simple cost effective and versatile, as only one motor is designed to perform all the movement in the reconfigurable joint.

5. Acknowledgements:

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6. References:

1. A. M. Djuric, R. Al Saidi, and W. ElMaraghy, "Global Kinemtaic Model for n-DOF Reconfigurable Machinery Structue," Automation Science and Engineering (CASE), 2010 IEEE Conference on , vol., no., pp.804,809, 21-24 Aug. 2010.
2. Mehrabi, M. G., Ulsoy, A. G., and Y. Koren, "Reconfigurable Manufacturing Systems: Key to Future Manufacturing," Journal of Intelligent Manufacturing 11 (2000), 403-419
3. Farhad Aghili, and Kourosh Parsa, "A Reconfigurable Robot With Lockable Cylindrical Joints," Robotics, IEEE Transactions on , vol.25, no.4, pp.785,797, Aug. 2009
4. Pakpong Jantapremjit, and David Austin, "Design of a Modula Self- Reconfigurable Robot," P roc. 2001 Australian Conference on Robotics and Automation, Sydney, 14-15 November 2001.
5. J. Denavit, and R. S. Hartenberg, " A Kinematic Notation for Lower-Pair Mechanisms Based on Matrices," Trans ASME J. Appl. Mech 23: 215–221
6. Toshio Fukuda, and Yoshio Kawauchi, "Cellular Robotic System (CEBOT) as One of the Realization of Self-Organizing Intelligent Universal Manipulator," Robotics and Automation, 1990. Proceeding., 1990 IEEE International Conference on , vol., no., pp.662,667 vol.1, 13-18 May 1990.
7. Wei-Min Shen, Yimin Lu, and Peter Will, "Hormone-Based Control for Self- Reconfigurable Robot," Proceedings of the fourth international conference on Autonomous agents. ACM, 2000.
8. Behrokh Khoshnevis, Robert Kovac, Wei-Min Shen, and Peter Will, "Reconnectable Joints for Self-Reconfigurable Robot,"
9. Satoshi Murata, Haruhisa Kurokawa, Eiichi Yoshida, Kohji Tomita, and Shigeru Kokaji, "A 3-D Self-Reconfigurable structure," Proceeding of the 1998 IEEE International Conference on Robotics and Automation, pages 432-439, 1998.
10. Andres Castano, Alberto Behar, and Peter M. Will, "The Conro Modules for Reconfigurable Robot," IEEE/ASME Trans. Mechaton., vol. 7, no. 4, pp. 403-409, Dec 2002.
11. Daviv Hjelle, and Hod Lipson, "A Robotically Reconfigurable Truss," Reconfigurable Mechanisms and Robots, 2009. ReMAR 2009. ASME/IFToMM International Conference on. IEEE, 2009.
12. Y. Koren, U Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy, and H. Van Brussel, "Reconfigurable Manufacturing Systems," Annals-Manufacturing Technology 48.2 (1999): 123.
13. Mehrdad R. Kermani, Mehrdad Moallem, and Ranji V. Patel. Applied Vibration Suppression Using Piezoelectric Materials (Nova Publishers, 2008).
14. Z. Li, W. Melek, and C. M. Clark, "Development and Characterization of a Modular and Reconfigurable Robot," Proceeding of the International Conference on Changeable, Agile, Reconfigurable and Virtual Production. 2007.

15. S. Tabandeh, C. Clark, and W. Melek, " Task-Based configuration Optimization of Modular and Reconfigurable Robot using a Multi-Solution Inverse Kinematics Solver," Proceeding of 2nd international conference on changeable, agile, reconfigurable and virtual production (CARV 2007).