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DK Model Equations of a Fixed Axis Robot Arm

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ABSTRACT

This paper features the development of a kinematic model for a 5-axis stationary articulated robot arm and this model is used to do a pick and place task using a graphical user interface developed in C++ language.

Keywords: *Robot, DH, LCD, KPT, Axes, Arm matrix, Control, Articulation, Kinematics.*

1. INTRODUCTION

Robotics is an interdisciplinary field which mixed various engineering disciplines into one. Keeping in pace with the current technology, we have designed and fabricated a stationary 5-axes articulated robot as shown in Fig. 1. This fabricated unit is used to perform a kinematic model which is further used to perform a PNP task without human intervention using sensors.

The paper is organized as follows. In section 2, a brief introduction about the designed and fabricated robotic manipulator is given. Sections 3 and 4 discusses about the development of the direct kinematic model. Finally, the conclusions are presented in the last section followed by the references.

2. DESIGNED & FABRICATED SYSTEM

The simulated robot is a 5 DOF stationary articulated robot arm having base, shoulder, elbow, tool pitch and tool roll and consisting of only rotary joints [1]. The design consisted of three parts, viz., mathematical modelling, mechanical design, electronic design and the software design. There are 5 joints, 5 axis (3 major axes - base, shoulder elbow: to position the wrist and 2 minor axis - pitch and roll: to orient the gripper in the direction of the object). Since n = 5 ; 20 kinematic parameters are to be obtained and 6 unit frames are to be attached to the various joints [2] as shown in the link coordinate diagram in Fig. 2.

The vector of joint variables is given by [1]

$q = \{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5\}^T$.

The vector of joint distances are given by [1]

$d = \{d_1, d_2, d_3, d_4, d_5\}^T = \{25, 0, 0, 0, 15\}^T$ cm .

The vector of link lengths are given by [1]

$a = \{a_1, a_2, a_3, a_4, a_5\}^T = \{0, 23, 22, 8, 0\}^T$ mm.

The vector of link twist angles are given by [1]

$\alpha = \{\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5\}^T = \{90°, 0, 0, 90°, 0\}^T$.

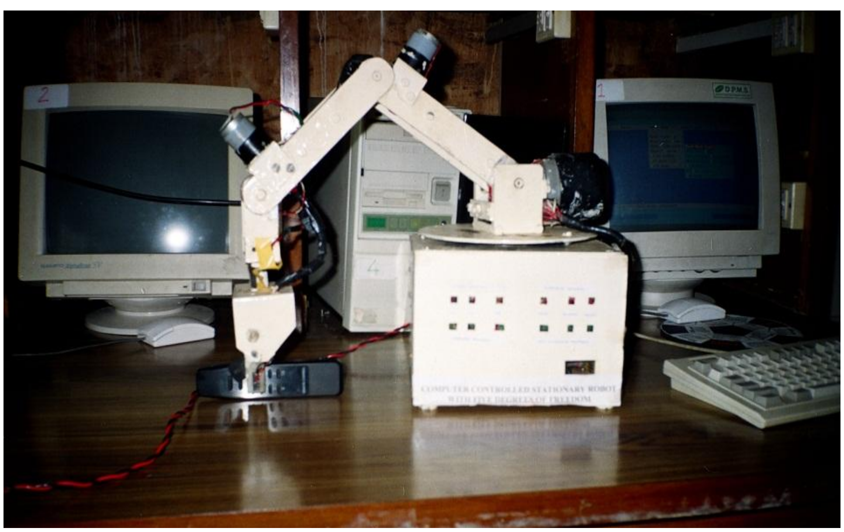

Fig. 1. Indigenously developed 5-axes articulated robot

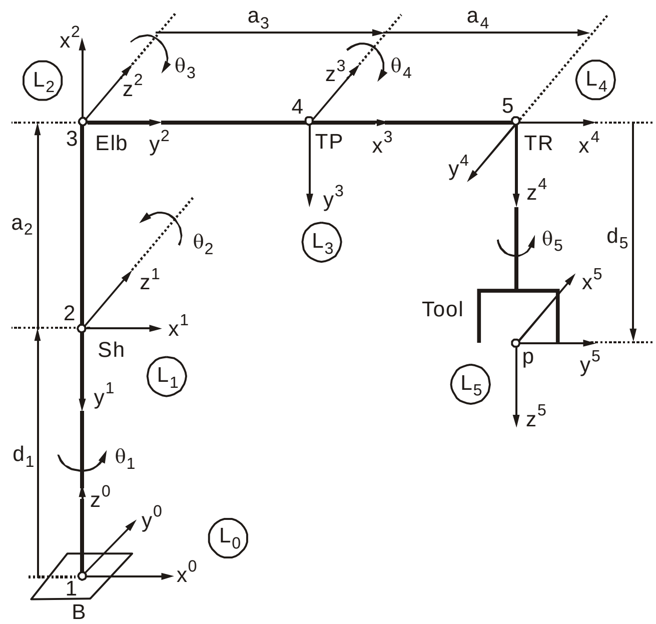

Fig. 2. Link coordinate diagram of the robot arm

There are 20 kinematic parameters and 6 RHOCF's in the Link Coordinate Diagram (LCD) shown in Fig. 2. Each joint has its own set of sprocket and chains which then determine the joint angle precision. There are three links a2 and a3 and a4. The height of the shoulder from the base is d1 and the tool / gripper length is d5. d1 is the height of the shoulder from the base which can be seen in Fig. 4 [1].

3. DIRECT KINEMATIC ANALYSIS ALGORITHM & THE KINEMATIC MODEL

Given the joint variable vector q (θ for joint) and the Geometrical Link Parameters (GLP-physical dimensions of the robot arm**:** constant for a given robot), finding the position p of the tip of the gripper and the orientation R of the gripper of the robot arm w.r.t. base of the robot from the reference position is called as *direct kinematics* as shown in Fig. 3. To solve the DKP means to find the p and R of the tool w.r.t. base [1].

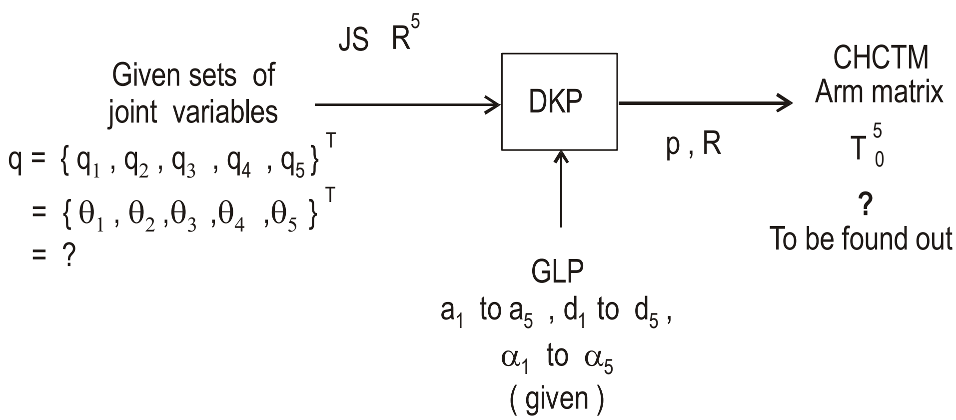

Fig. 3. Direct kinematic input-output model of the designed robot arm

To find the position and orientation of the robot arm means, we have to find a matrix called as the *arm matrix*, i.e., the composite homogeneous coordinate transformation matrix, which is a (4 × 4) matrix. How does this matrix give the position and orientation of the robot w.r.t. base from the reference position? The 1st three columns gives the three possible orientations (Yaw, Pitch, Roll) of the gripper and the last column gives the position of the tip of the gripper 'p' , thus solving the DK problem. If we give this matrix as input to the robot, the robot will go and stop in that particular position and in that particular orientation [1].

Table I. Kinematic parameter table of the developed robot

Type	θ_k	d_k	a_k	α_k	SHP
Base	θ_1	d_1	0	– 90°	0
Shoulder	θ_2	0	a_2	0	– 90°
Elbow	θ_3	0	a_3	0	π / 2
Tool pitch	θ_4	0	a_4	– 90°	0
Tool roll	θ_5	d_5	0	0	– 90°

4. DIRECT KINEMATIC ALGORITHM

The DK algorithm (drawing of the LCD) is as follows [1].

- Draw the SLD of the designed robot with links represented by straight lines; joints by small circles called as nodes [6].
- Using 1st pass of DH algorithm, assign (5 + 1) = 6 right handed orthonormal coordinates L_0 to base, L_1 to shoulder, L_2 to the elbow, L_3 to the tool pitch, L_4 to tool roll, L_5 to the tip of the gripper, 'p' as shown in the Fig. 2.
- Using 2nd pass of the DH algorithm, find the (4 × 5) = 20 KP's and obtain the kinematic parameter table KPT as shown in the Table I [5].
- Put k = 1 to 5 and the different rows of the KPT in the general link coordinate transformation matrix T_{k-1}^{k} and obtain the various fundamental homogeneous coordinate transformation matrices T_0^1, T_1^2, T_2^3, T_3^4, T_4^5.
- Since n > 4, partition the arm matrix T_0^5, at the wrist so that we get two wrist partitioned matrices. One which gives the position and orientation of the wrist w.r.t. the base, i.e., T_0^3 and the other which gives the position and orientation of the gripper w.r.t. the wrist, i.e., T_3^5.
- Multiply the first three fundamental HCTM's T_0^1, T_1^2, T_2^3. Obtain the arm matrix $T_0^3 = T_0^1\ T_1^2\ T_2^3$,
- Multiply the next two fundamental HCTM's T_3^4, T_4^5. Obtain the arm matrix $T_3^5 = T_3^4\ T_4^5$.
- Multiply the two wrist partitioned matrices, T_0^3 and T_3^5 to obtain the output of direct kinematic problem, i.e., T_0^5.
- Substitute the soft home position - SHP angles (last column of KPT) in the computed arm matrix T_0^5 and compute T_0^5 in the home position. Verify the LCD & get the arm equations, which are very useful in the kinematic modelling.
- The arm matrix is as follows [1].
- The arm matrix is divided into three parts, viz., first partitioned matrix T_0^3, second partitioned matrix T_3^5 and the final arm matrix T_0^5.
- To find the position p and orientation R of gripper w.r.t. base , use successive HCTM' s starting from the tip of the gripper and ending at the base.

$$T_{Base}^{Tool} = T_{Base}^{Shoul}\ T_{Shoul}^{Elbow}\ T_{Elbow}^{Pitch}\ T_{Pitch}^{Roll}\ T_{Roll}^{Tip} \tag{1}$$

$$T_0^5 = T_0^1\ T_1^2\ T_2^3\ T_3^4\ T_4^5 \tag{2}$$

$$T_0^5 = \left[T_0^1\ T_1^2\ T_2^3\right]\left[T_3^4\ T_4^5\right] \tag{3}$$

$$T_0^5 = T_0^3\ T_3^5 \tag{4}$$

$$T_{Base}^{Tool\text{-}tip} = T_{Base}^{Wrist\ (Pitch)}\ T_{Wrist\ (Pitch)}^{Gripper\text{-}tip} \tag{5}$$

$$f\begin{pmatrix}\theta_1 & \theta_2\\ \theta_3 & \theta_4\\ & \theta_5\end{pmatrix} \quad f\begin{pmatrix}\text{major axes}\\ \theta_1\ \ \theta_2\ \ \theta_3\end{pmatrix}$$

$$f\begin{pmatrix}\text{minor axes}\\ \theta_4\ \ \theta_5\end{pmatrix}$$

Computation of the first wrist partitioned arm matrix is obtained as follows [1].

$$T_0^3 = T_0^1\ T_1^2\ T_2^3 \tag{6}$$

$$\begin{bmatrix} C_1 & 0 & -S_1 & 0 \\ S_1 & 0 & C_1 & 0 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} C_2 & -S_2 & 0 & a_2C_2 \\ S_2 & C_2 & 0 & a_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_3 & -S_3 & 0 & a_3C_3 \\ S_3 & C_3 & 0 & a_3S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} =$$

$$\begin{bmatrix} C_1\,C_2 & -C_1\,S_2 & -S_1 & a_2C_1C_2 \\ S_1\,C_2 & -S_1\,S_2 & C_1 & a_2S_1C_2 \\ 0 & -C_2 & 0 & d_1 - a_2S_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} C_3 & -S_3 & 0 & a_3C_3 \\ S_3 & C_3 & 0 & a_3S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1(C_2C_3-S_2S_3) & -C_1(S_2C_3+C_2S_3) & -S_1 & C_1\{a_3(C_2C_3\text{-}S_2S_3)+a_2C_2\} \\ S_1(C_2C_3-S_2S_3) & -S_1(S_2C_3+C_2S_3) & C_1 & S_1\{a_3(C_2C_3\text{-}S_2S_3)+a_2C_2\} \\ -(S_2C_3+C_2S_3) & -(C_2C_3+S_2S_3) & 1 & d_1-a_2S_2-a_3(S_2C_3+C_2S_3) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^3 = \begin{bmatrix} C_1\,C_{23} & -C_1\,S_{23} & -S_1 & C_1(a_2C_2 + a_3C_{23}) \\ S_1\,C_{23} & -S_1\,S_{23} & C_1 & S_1(a_2C_2 + a_3C_{23}) \\ -S_{23} & -C_{23} & 0 & d_1 - a_2S_2 - a_2S_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (7)$$

This matrix T_0^3 gives position and orientation of the wrist (pitch) coordinate frame L_3 w.r.t. the base frame L_0.

To check this whether the matrix obtained is correct or not, evaluate it at the Soft Home Position [SHP] by putting the values of the angles given in the last column of KP table in T_0^3 [7] ;

i.e., put $q = [\,0\,, -90°\,, 90°\,]^T$ which is $= \{q_1\,, q_2\,, q_3\,\}^T$ in the computed T_0^3 matrix, we get ;

$$T_0^3\,(\text{home}) = \begin{bmatrix} 1 & 0 & 0 & a_3 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & d_1 + a_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^3 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & p_1 \\ R_{21} & R_{22} & R_{23} & p_2 \\ R_{31} & R_{32} & R_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (8)$$

Note that this is coincident from the LCD shown in Fig. 2, hence the LCD is also verified.

The computation of the second wrist partitioned arm matrix is obtained as follows [1].

$$T_3^5 = T_3^4\;T_4^5 \qquad (9)$$

$$T_3^5 = \begin{bmatrix} C_4 & 0 & -S_4 & a_4d_4 \\ S_4 & 0 & C_4 & a_4S_4 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_5 & C_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_4C_5 & -C_4S_5 & -S_4 & a_4C_4 - d_5S_4 \\ S_4C_5 & -S_4S_5 & C_4 & a_4S_4 + d_5C_4 \\ -S_5 & -C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (10)$$

This matrix T_3^5 gives the position and orientation of the tip coordinate frame L_5 w.r.t. the wrist coordinate frame L_3.

To check this whether the matrix obtained is correct or not, evaluate it at the Soft Home Position [SHP] by putting the values of the angles given in the last column of KP table in T_3^5, i.e., put $q = \{\,0\,, -90°\}^T = \{q_4\,, q_5\,\}^T$ in the computed T_3^5 , we get [8];

$$T_3^5\;(\text{home}) = \begin{bmatrix} 0 & 1 & 0 & a_4 \\ 0 & 0 & 1 & d_5 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^5 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & p_1 \\ R_{21} & R_{22} & R_{23} & p_2 \\ R_{31} & R_{32} & R_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

Note that this is coincident from the LCD. Thus, the LCD is also verified.

The computation of the final arm matrix/ CHCTM is obtained as follows [1].

To compute the final arm matrix ; multiply the two wrist partitioned matrices T_0^3 and T_3^5 given by Eqs. (7) and (10). Simplify the arm matrix by using some assumptions as

$$T_0^5 = T_0^3 \quad T_3^5$$

$$= \begin{bmatrix} C_1 C_{23} & -C_1 S_{23} & -S_1 & C_1(a_2C_2 + a_3C_{23}) \\ S_1 C_{23} & -S_1 S_{23} & C_1 & S_1(a_2C_2 + a_3C_{23}) \\ -S_{23} & -C_{23} & 0 & d_1 - a_2S_2 - a_2S_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} C_4C_5 & -C_4S_5 & -S_4 & a_4C_4 - d_5S_4 \\ S_4C_5 & -S_4S_5 & C_4 & a_4S_4 + d_5C_4 \\ -S_5 & -C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1C_{234}C_5 + S_1S_5 & -C_1C_{234}S_5 + S_1C_5 & -C_1S_{234} & C_1(a_2C_2 + a_3C_{23} + a_4C_{234} - d_5S_{234}) \\ S_1C_{234}C_5 - C_1S_5 & -S_1C_{234}S_5 - C_1C_5 & -S_1S_{234} & S_1(a_2C_2 + a_3C_{23} + a_4C_{234} - d_5S_{234}) \\ -C_5S_{234} & S_{234}S_5 & C_{234} & d_1 - a_2S_2 - a_3S_{23} - a_4S_{234} - d_5S_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^5 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & p_1 \\ R_{21} & R_{22} & R_{23} & p_2 \\ R_{31} & R_{32} & R_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

To check this matrix whether it is correct or not, evaluate it at SHP, by putting the SHP angles which are given in the last column of the KPT in this computed final arm matrix, T_0^5, i.e., $q = \{ q_1, q_2, q_3, q_4, q_5\}^T = \{ \theta_1, \theta_2, \theta_3, \theta_4, \theta_5\}^T = \{ 0°, -90°, 90°, 0°, 90° \}^T$ in T_0^5. Check that the norms of the rotation matrix of T_0^5. They are all unity [1].

This arm matrix T_0^5 given by Eqn. (12) is the output of direct kinematics of the designed five axes articulated robot arm, thus giving the position and orientation of the gripper w.r.t. base . The 1st three columns gives the orientation of the frame L_5 w.r.t. base, while the last column gives the position of the tip of the gripper p w.r.t. base, thus obtaining a unique direct kinematic model of the designed robot [1].

$$T_0^5(SHP) = \begin{array}{c} \\ x^0 \\ y^0 \\ z^0 \\ \\ \end{array} \begin{array}{c} \begin{array}{cccc} x^5 & y^5 & z^5 & p \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & a_3 + a_4 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & d_1 - a_2 - d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

Obtain the arm equations by equating the two matrices as

$$T_0^5 = T_0^5(SHP).$$

$$R_{11} = C_1C_{234}C_5 + S_1S_5 = 0$$

$$R_{21} = S_1C_{234}C_5 - C_1S_5 = 1$$

$$R_{31} = -C_5S_{234} = 0$$

$$R_{21} = -C_1S_5C_{234} + S_1C_5 = 1$$

$$R_{22} = -S_1S_5C_{234} - C_1C_5 = 0$$

$$R_{32} = S_{234}S_5 = 0$$

$$R_{31} = -C_1S_{234} = 0$$

$$R_{32} = -S_1S_{234} = 0$$

$$R_{33} = -C_{234} = -1$$

$$p_1 = C_1(a_2C_2 + a_3C_{23} + a_4C_{234} - d_5S_{234})$$

$$= a_3 + a_4$$

$p_2 \;=\; S_1\,(a_2C_2 + a_3C_{23} + a_4C_{234} - d_5S_{234}) = 0$

$p_3 \;=\; d_1 - a_2S_2 - a_3S_{23} - a_4S_{234} - d_5C_{234}$

$\;\;\;\;\;= \; d_1 + a_2 - d_5$

We get 12 kinematic non-linear equations in five unknowns (Base, Shoulder, Elbow, Pitch, Roll). The final arm matrix $T_{Base}^{Tool\text{-}tip}$ can be used to find the position and orientation of the robot arm by giving the values of the joint variables and the geometric link parameters, viz., a's and d's.

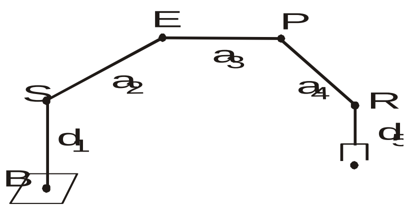

Fig. 4 One line diagram depicting the kinematic parameters of the designed robot

5. CONCLUSION

A indigenously designed and fabricated 5-axes articulated system was used to obtain the kinematic model of the same and was used to perform a successful pick and place task using a user-friendly developed graphical user interface and real time implementation.

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Dr. T.C.Manjunath was born in Bangalore, Karnataka, India on Feb. 6, 1967 & received the B.E. Degree (Bachelor of Engg.) from R.V. College of Engg. (Bangalore Univ.) in the year 1989, M.Tech. degree in Automation, Control & Robotics from the Govt.’s L.D. College of Engg. (Gujarat Univ.) in the year 1992 and Ph.D. in Systems & Control Engg. from the prestigious Indian Institute of Technology Bombay (IIT Bombay) in the year 2007 respectively. He has got a teaching experience of more than 23 long years in various engineering colleges all over the country (Karnataka, Gujarat, Maharashtra) and is currently working as **Principal** in **HKBK College of Engg.**, Bangalore, Karnataka, India. He has also worked as a Project Assistant and as a Research Engineer in the Systems and Control Engineering (IIT Bombay, India) and worked on control of space launch vehicles using FOS feedback technique in IITB. He has published a number of papers in various National, International journals and Conferences in India & abroad and published more than a **dozen textbooks**, notable among them being on Robotics, first one being Introduction to robotics, second one which has gone upto the fourth edition, titled, ‘Fast Track to Robotics’ and the third one, which has gone upto the fifth edition, titled, ‘Fundamentals of Robotics’ in 2 volumes, Vol.-1 and Vol.-2 along with a CD which contains about 200 C / C++ programs for performing various simulations on robotics. He has also published a research monograph in the International level from the Springer-Verlag publishers based on my Ph.D. thesis topic titled, “Modeling, Control and Implementation of Smart Structures”, Vol. 350, LNCIS, costing **114.95 Euros**. He is a member of IEEE for the past 12 years, SPIE student member and IOP student member for 4 years, life member of ISSS (India), life member of the ISTE (India), life member of ISOI (India), life member of SSI (India), life member of the CSI (India), Sr. Member of IACST (Singapore) and life member cum fellow of the IETE (India). He has also presented a number of guest lectures and seminars in many institutions across the country and participated in more than 2 dozen CEP / DEP courses, seminars, workshops, symposiums and also conducted a few courses in the institutions where he has worked. He was awarded with the “Best research scholar award in engineering discipline” for the academic year 2006-07 from the Research Scholars Forum (RSF) from Indian Institute of Technology Bombay (IITB). This award was presented in recognition of the significant contribution to the research (amongst all the researchers in all disciplines) in IIT Bombay. Also, he was conferred with the best paper awards in a number of conferences. he was also instrumental in getting Research centres along with M.Tech programs in the colleges where he has worked so far. He was also responsible for getting AICTE grants under MODROB scheme for the development of the Robotics & Mechatronics Labs. Apart from which, he has brought a number of grant-in-aids for the conduction of various events like workshops, conferences, seminars, projects, etc, wherever he has worked. He has visited Singapore, Russia, United States of America, Malaysia, Taiwan, Japan, Canada, Nepal and Australia for the presentation of my research papers in various international conferences. His biography was published in 23rd edition of Marquis’s Who’s Who in the World in the 2006 issue. He has also guided more than 3 dozen projects (B.Tech. / M.Tech.) in various engineering colleges where he has worked so far, apart from guiding a couple of research scholars who are doing Ph.D. in various universities under his guidance. Many of his guided projects, interviews, the events what he had conducted have appeared in various national newspapers and magazines. He has also reviewed many research papers for the various national & international journals & conferences. He has also organized a number of state & national level sports tournaments like yogasana, chess, cricket, etc. He is also an editorial board / advisory board / reviewer member on many of the national & international Journals. He has also served on the advisory / steering / organizing committee member of a number of national & international conferences. He has given many keynote / invited talks / plenary lecturers in various national & international conferences and chaired many sessions, was the judge & was the chief guest on various occasions. He has given a number of guest / expert lectures in various colleges across the country. He has also conducted / organized / convened / coordinated more than 4 dozen courses / workshops / technical paper fests, Student level competitions, etc., in various engineering colleges where he worked so far.