www.ijecs.in
*International Journal Of Engineering And Computer Science ISSN:2319-7242*
*Volume – 5 Issue -02 February, 2016 Page No. 15749-15754*

# Control algorithm for SISO case using F O S with modeling in Simulink

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**Abstract:** ***Vibration control plays a very important role in the modern day world especially in control of earthquakes & in aerospace engineering. With reference to this, research is being carried out in this exciting field of smart intelligent structures. Control of vibrations in smart intelligent structures for a single input single output case using fast output sampling method is presented in this paper using the modeling done in Matlab-Simulink environment. The model is run & the simulation results are observed on the scopes. The simulation results show the effectiveness of the method presented in this paper, how the vibrations are suppressed in a shorter time.***

**Keywords:** Smart structures, Fast output sampling, Vibration control, Beams, Sensors, Actuators.

## 1. Introduction

A smart material is defined as any material that is capable of being controlled such that its response and properties change under a stimulus. A smart structure or system is capable of reacting to stimuli or the environment in a prescribed manner. Smart Materials and Structures is committed to the understanding, expansion and dissemination of knowledge in this subject matter. To this end, the Journal publishes articles in the following areas [60]:

- Smart materials development and application—including, but not limited to, shape memory alloys and polymers, electro and magnetorheological materials, piezoelectrics, ferroelectrics, piezomagnetics, electro and magnetostrictive materials, thermoelectrics, photovoltaics, electro and magnetocaloric materials, electrochromics, IPMCs, electroactive polymers, energy storage materials, ferroelectrics, self-healing materials and multifunctional materials in general [60].
- Smart materials utilized as sensors and actuators with applications at any scale [59].
- Adaptive structural systems, actively controlled structures with smart materials and other non-traditional actuators [58].
- Sensor and sensor networks for smart materials and structure applications, processing of sensor information for adaptive control or structural health monitoring as well as integration of these sensor networks into materials and structures [57].
- Smart optical materials for modification in spectral shifts and refractive index shift [56].
- Structural health monitoring with applications to ground vehicles, aircraft and civil infrastructure [55].
- Intelligent systems, integrated with sensors, actuators and controllers, applied to automation and robotic systems that utilize smart material systems [54].
- Energy harvesting systems including modelling, applications and implementation issues [53].

Smart materials such as sensors & actuators together integrated or embedded into the structure are what is called a "Smart Structure" and are often called as the intelligent structures, which are used for control of vibrations in structures & earthquakes [52]. Smart materials are a subset of the smart structure [1]. Thus, a smart structure is a distributed parameter system that employs sensors & actuators at different finite element locations on the beam and makes use of sophisticated feedback controllers that analyze the responses obtained from the sensors and use different control logics to command the actuators to apply localized strains to the plant to respond in a desired fashion. Smart structures have also got the capability to respond to the changes in the environment on the plant, whether internal or external such as load changes or temperature changes [2]. A smart structure system comprises of 4 important sub-parts such as sensors, controller, actuators and the plant (flexible beam), whose condition is to be controlled [53]. Each component of this smart structure system has a certain functionality and the entire sub-systems are integrated to perform a self-controlled smart action, similar to a living creature who can "think", make judgment and take actions on own at the appropriate time, thus inducing the smart & intelligentness [3].

The paper is organized as follows. A brief review about the smart structures is presented in the introductory section. The control law used in the research work is presented in section 2 followed by the control simulations in section 3. Justifications of the simulation results are presented in section 4. The section 5 presents the conclusions of the work done. This is followed by the references & the author biographies.

## 2. Concept of the control law of FOS

The concept of how the control law is developed using the fast output sampling feedback control technique is shown in the Fig. 1 as [9]

DOI: 10.18535/ijecs/v5i2.16

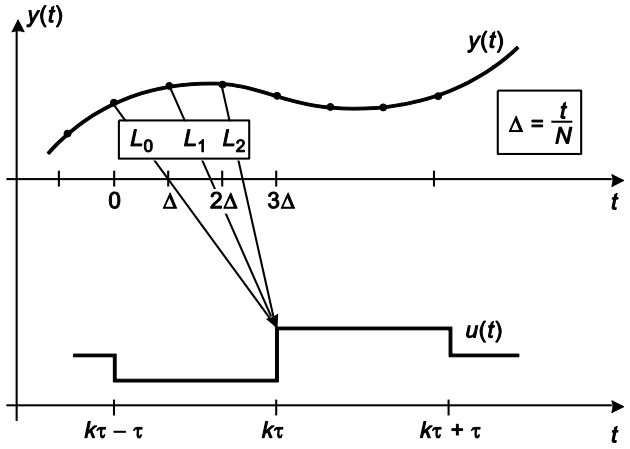


Fig. 1 : FOS method (graphical illustration)

The block diagram shown below in Fig. 2 gives overall information about the control strategy development as a dual feedback loop is incorporated [10].

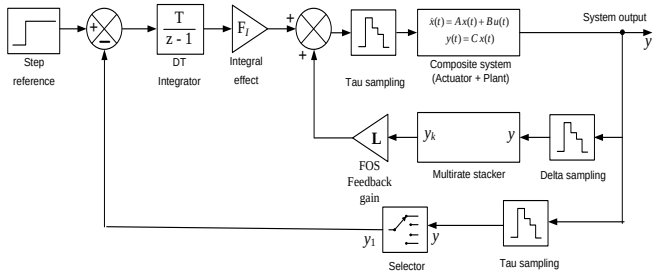


Fig. 2: FOS f/b method applied to the smart beam – Block diagram

The plant, i.e., the beam is divided into 4 finite elements as shown in the figure below, at the same time, the dimensions of the flexible beam is also shown in the table below, which is being used for simulation purposes [51].

| **Physical Parameters** | **Aluminum Beam** | **Piezoelectric sensor / actuator** |
|---|---|---|
| Length | $L_b$ = 0.3 m | $L_p$ = 0.075 m |
| Width | $b$ = 0.025 m | $b$ = 0.025 m |
| Thickness | $t_b$ = 1.2 m | $t_p$ = 1.2 m |
| Young's Modulus | $E_b$ = 193 GPa | $E_p$ = 68 GPa |

Table 1 : Dimensions-Properties of Al Beam & PZT Sensor & Actuator

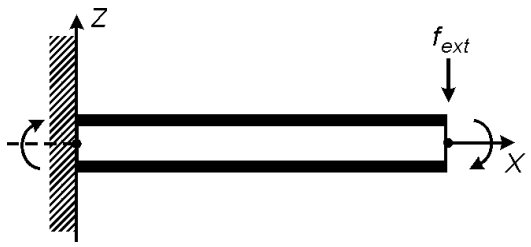


Fig. 3: A regular flexible beam and a smart aluminum cantilever beam bonded with surface mounted piezoelectrics

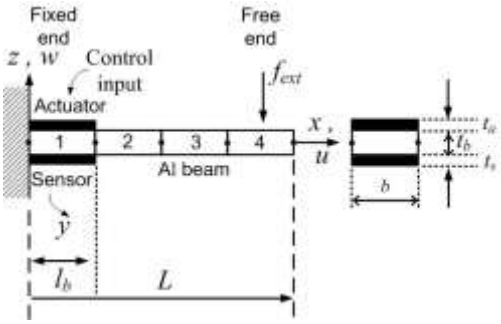


Fig. 4 : PZT placed at FE position 1, fixed end

The single input single output state space model (state equation and the output equation) of the smart structure developed for the system shown in Fig. 4 starting from the first principles is given by [50]

$$\dot{\mathbf{x}} = \mathbf{A}\,x(t) + \mathbf{B}u(t) + \mathbf{E}r(t),\ y(t) = \mathbf{C}^T\mathbf{x}(t) + \mathbf{D}u(t),$$

with

$$\mathbf{A} = \begin{bmatrix} 0 & I \\ -\mathbf{M}^{*-1}\mathbf{K}^* & -\mathbf{M}^{*-1}\mathbf{C}^* \end{bmatrix}_{(4\times 4)},\ \mathbf{E} = \begin{bmatrix} 0 \\ \mathbf{M}^{*-1}\mathbf{T}^T\mathbf{f} \end{bmatrix}_{(4\times 1)}$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ \\ \mathbf{M}^{*\,-1}\mathbf{T}^T\mathbf{h} \end{bmatrix}_{(4\times 1)},\quad \mathbf{C}^T = \begin{bmatrix} 0 & \mathbf{p}^T \end{bmatrix}_{(1\times 4)},\quad \mathbf{D} = \text{Null Matrix},$$

where the parameters $r(t)$, $\mathbf{u}(t)$, $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, $\mathbf{D}$, $\mathbf{E}$, $\mathbf{x}(t)$, $y(t)$ represents the external force input, the control input, system matrix, input matrix, output matrix, transmission matrix, external load matrix, state vector and the system output (sensor output) [49]. This model is used for developing the controller in simulink environment [48].

If the controller is to be implemented digitally on a computer, then a sampled data controller has to be designed anyway, and in this section it is shown how a robust sampled-data state feedback gain with zero-order hold can be realized by a fast output-sampling controller [55] [56] [57]. In this type of control law as shown in Fig. 1, the value of the input at a particular moment depends on the output value at a time prior to this moment (namely at the beginning of the period) [50]. Werner and Furuta [55] [56] [57] have shown that the poles of the discrete time control system could be assigned arbitrarily (within the natural restriction that they should be located symmetrically with respect to the real axis) using the fast output sampling technique [51]. Since the feedback gains are piecewise constants, their method could easily be implemented, guarantees the closed loop stability and indicated a new possibility [14]. Such a control law can stabilize a much larger class of systems [49]. The control objective is to sample the output $y(t)$ at a faster rate, i.e., at $\Delta$ intervals and applied to the controller at $\tau$ interval which is more advantageous [52]. At the same time, the states are not needed for feedback in the FOS case and here, we realize the state feedback using the output feedback [15]. The output is sampled at a faster rate here [47].

## 3. Matlab-Simulink Environment Design

Simulink model is developed using Matlab 12-Simulink environment & the basic functions such as the step signals,

comparators, integrators, multiplexers & the control loops with the control algorithm being put in the loop inside the matrix. The developed Simulink model is shown in figure below [46].

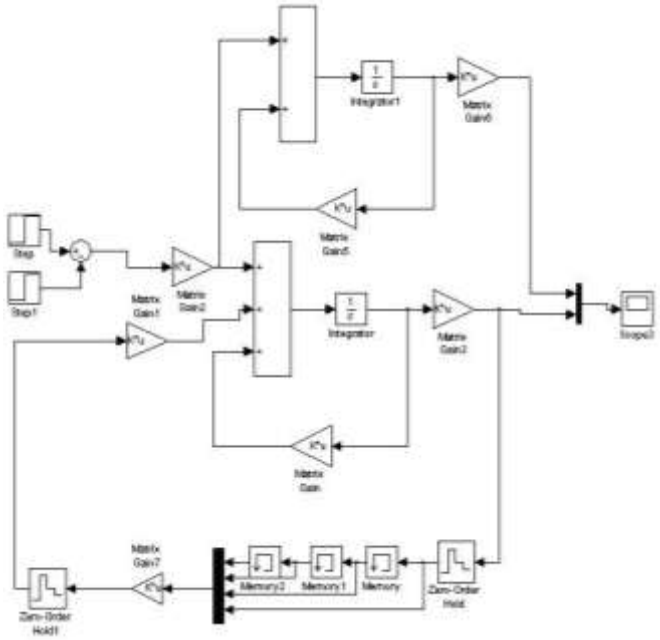

Fig. 5 : Developed Simulink model for FOS controller design

A mathematical model for the considered smart beam was formulated and used for the vibration control purposes in our research work [45]. First, the beam model is obtained using fundamental principles, then the state space model, finally the Simulink model is developed in Matlab-Simulink environment [44]. The beam is excited by an exciter & is then subjected to vibrations [43]. These vibrations are sensed by the sensor. The sensor is used to sense the vibrations in the beam and then send it to the FOS controller [42]. Here, the signals are evaluated and corresponding destructive signals are generated by the actuator to curb down the vibrations [41]. Finally, this is given as input to the actuator will induce destructive anti-vibration signals in the beam to reduce the overall vibration signature of the beam [40]. Controller has been designed for the smart aluminum beam using the FOS feedback control technique for the developed state space model of the smart beam to suppress the first few vibratory modes only (first two only as these are the most dominant ones as the other modes are not that efficient and do not contribute much to the vibration suppression) [39]. The various responses are observed with & without the controller [38].

## 5 Justifications of the simulated results

A state feedback gain for the discrete model is obtained such that its poles are placed inside the unit circle and the responses have a very good settling time [37]. Responses are also simulated for the plant without control and are compared with the control to show the control effect [36]. The open loop responses take more time to settle & the amplitude is very high than compared to the closed loop counterparts [35]. From the developed Simulink model's output results, it was observed that without control the transient response of the system was predominant and with control, the vibrations are suppressed, i.e., attenuated [34]. It was seen that the tip displacement also is well controlled and is within limits [33]. The designed FOS feedback controller requires constant gains and hence may be easier to implement in real time if some experimentation work is taken up [32]. The simulation results are shown in the figures 6 & 7 respectively [31].

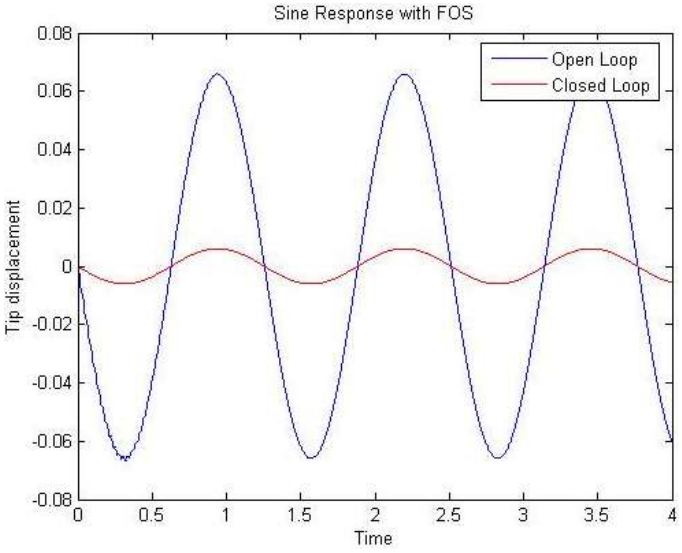


Fig. 6 : OL & CL responses with and w/o FOS-control

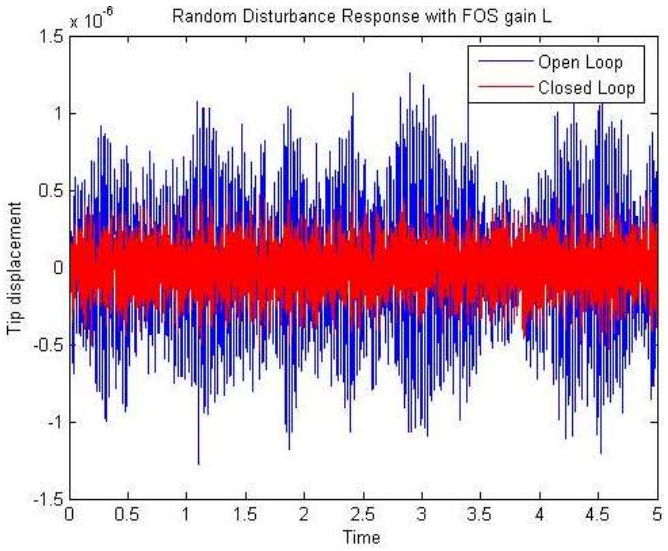


Fig. 7 : OL & CL random signal responses with & w/o FOS-control

## 5 Conclusions

In this paper, control of vibrations in smart intelligent structures for a single input single output case using fast sampling method was presented using the controller designed in the simulink [1] - [10]. The simulation results show the effectiveness of the method developed for vibration suppression [11] - [20]. Thus, an integrated finite element model to analyze the vibration suppression capability of a smart cantilever beams with surface mounted piezoelectric devices is presented in this paper using the concept of FOS [21] - [30].

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## BIOGRAPHIES

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., B'lore) in the year 1989, M.E. degree in Automation, Control & Robotics from the prestigious Govt.'s LD College of Engg., (Gujarat Univ., Ahmadabad) in the year 1992 and Ph.D. in Systems & Control Engineering from the prestigious Indian Institute of Technology Bombay (IIT Bombay) in the year 2007 respectively. He has got a teaching (academic), research & administrative experience of more than 25+ years in various engineering colleges all over the country (Karnataka, Gujarat, Maharashtra). He has worked in the levels of Lecturer-Asst. Prof., PG Coordinator, Prof-i/c HOD-Prof. & Head, Director-Research, i/c Principal & as Full time Principal (> 6 yrs-Atria IT, BTLITM, HKBKCE, Dr. AIT) in the various institutions where he has worked so far. Currently, he is working as the Principal of the famous NICE group's 'Nandi Institute of Technology & Management Sciences' in Bengaluru, Karnataka. 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 ('*Introduction to robotics*' - 1st edition, '*Fast Track to Robotics*' - 4th edition, '*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 – 5th edition, '*Examination Security System - Design & Development of Examination Mechanism Using Electronic Box*' from Germany costing around 49 Euros). He has also published a number of '*book chapters*' in various edited books from renowned publishers. He has also published a research monograph in the International level from the Springer-Verlag publishers (Europe) based on his Ph.D. thesis topic titled, "*Modeling, Control and Implementation of Smart Structures*", Vol. 350, LNCIS, costing 114.95 Euros. He is a member of 21 professional societies. Some of them are ... He is a member of IEEE for the past 13 years (currently Sr. Member), Sr. member of IIIE, SPIE student member and IOP student member for 4 years, life member of ISSS (India), life member of additive manufacturing society of India (LMAMSI), life member of the ISTE (India), life member of ISOI (India), life member of SSI (India), life member of the CSI (India), Life member of IMAPS, Sr. Member of IACST (Singapore) and life member cum fellow of the IETE (India), AMSI, Chartered Engineer from IE (I) and Fellow of the Institute of Engineers (FIE). He has given a number of guest lectures / expert talks and seminars in many institutions across the country and participated in more than 2 dozen CEP / DEP courses, seminars, workshops, symposiums, besides conducting a few courses in the institutions where he worked. He was awarded with the "Best research scholar award in engineering discipline" for the academic year 2006-07 for the entire institute 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 conferred with the prestigious Rajiv Gandhi Education Excellence Award, Rashtriya Vidya Gaurav Gold Medal Award & International educational excellence award (in recognition of sterling merit excellence performance and outstanding contribution for the progress of the nation & world-wide) from New Delhi in the year 2013 w.r.t. his achievements in the field of education, academics, administration & research. He was also instrumental in getting Research centres (12 nos.) along with M.Tech. programmes & new UG programmes in the colleges where he has worked so far as the administrative head. He was also responsible for getting AICTE grants under MODROB scheme for the development of the Robotics & Mechatronics Labs in one of the colleges where he worked. Apart from which, he has brought a number of grant-in-aid for the

conduction of various events like workshops, conferences, seminars, projects, events, etc., wherever he has worked [from VTU, DST, IETE, CSI, IEEE, IE(I), VGST, KSCST, Vodafone, Uninor, etc.] from different sources. He has visited Singapore, Russia, United States of America, Malaysia and Australia for the presentation of his research papers in various international conferences abroad. 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 2 dozen projects (B.E. / B.Tech. / M.E. / M.Tech.) in various engineering colleges where he has worked, 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 state & national level newspapers and magazines (more than 110 times). He has also reviewed many research papers for the various national & international journals & conferences in India & abroad (more than 5 dozen times). He has also organized a number of state & national level sports tournaments like yogasana, chess, cricket, volleyball, etc. He is also an editorial board / advisory board / reviewer member and is on the panel of 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, special invitee, guest of honor & was the chief guest on various occasions. He has also conducted / organized / convened / coordinated more than 175+ courses / workshops / STTP's / FDP's / Technical paper fests, Student level competitions & Symposiums, etc., in various engineering colleges where he worked so far. He has also taken many administrative initiatives in the college where he has worked as HOD, Principal & also where he is currently working as Principal, besides conducting all the semester university exams successfully as chief superintendent, deputy chief superintendent, squad member, etc. Some of the special administrative achievements as HOD, Principal & Head of the Institution are …. He improved the results of the various branches in East West Inst. of Tech. / New Horizon College of Engg. / Atria Inst. of Tech. / BTL Inst. of Tech. / HKBK College of Engg. / Dr. Ambedkar Inst. of Tech. He gave more importance to the development of in-house projects for the final years. He has also He motivated many of the faculties to take up take up consultancy works & did it efficiently, so that the college got some good income. He made the faculties to take up research (Ph.D) work or do M.Tech. by compelling them constantly to purse for higher studies. As an administrative head, he made the faculties to publish paper in either national / international journals & conferences at least one in an academic year. He started the student chapters in all the branches such as IETE, IEEE, ISTE, CSI, SAE, ISSS, ISOI & also conducted a number of events under their banners. He brought in power decentralization in the institute by developing the habit of making coordinator-ships for various works, getting the work done by monitoring and following it up successively. He was also involved in TEQIP-2 process in Dr. AIT along with the development of many of the autonomy works. He conducted a number of exams from public sectors & private sectors such as GATE exams, CET / COMED-K, KPSC, Police Exams, Inst. of Civil Engineer exams & conducted a number of state & national level examinations like Defense, PG entrance exams, Medical, KPTL in the college so that the college could get some revenue (under the banner of revenue generation scheme). He started the weekly monitoring of the staff & students. He developed the counseling of student data booklets & that of the faculty work-books. All the laboratory manuals were developed in-house, printed & given to the students (both in the hard as well as in the soft copy). He used to conduct the academic & governing council meetings regularly along with the HOD's meetings time to time. He had looked after the NBA process in Fr. CRCE, BTLITM, HKBKCE & in Dr. AIT. He conducted the prestigious 7th IETE ICONRFW & the 28th Karnataka State CSI Student Convention. He introduced the scheme of best lecturer award / best HOD award / best non-teaching award / service awards concept / Principal cup / Departmental cup, etc. in the colleges where he worked as administrative head. He created a record placement of more than 600 students in Atria Inst. of Tech. / BTLITM & in HKBKCE with the help of the placement department. He helped the management to fill up many of the student admissions in the first year of UG (B.E.) & in PG (M.Tech.) course. He created a number of hobby-clubs, EDC cells, Innovation & Incubation centres, centre of excellences in the institute for the staffs & students to work towards development of prototypes, models, and projects. He started the faculty seminar series in the institute so that every faculty gives a lecture of 45 mins with 15 mins discussion at least once in a month. He introduced the concept of coaching class / tutorial classes for the weak students & remedial class concept for the failed students, which yielded successful results apart from the training of top 10 students for getting ranks (9th / 3rd Rank). He made the students to get university ranks in BTL & HKBKCE in UG stream. He started certificate oriented courses of 3 months & 6 months for the various types of people, especially on Saturdays & Sundays. He made the students to participate in competitions outside the college & win a number of prizes, brought laurels to the institution. He helped the students to get some financial assistance using sponsors for the cultural events. He brought a grant of nearly Rs. 3 crore till date in the various organizations where he has worked so far with help of faculties. He developed the Innovation & Entrepreneurship Development Cell in HKBKCE & did a number of programs under its belt. He was responsible for some of the UG students of HKBKCE to make them establish a start-up company in the college itself by name '*pentaP systems*'. He made more than one dozen MOU's with reputed firms & sectors with the college and utilized all the advantages of the signed MOUs with the companies. He streamlined many of the process in the office level & that of the departmental level by developing new formats for the smooth conduction of various processes along with excellent documentation. He developed the culture of making up of small / mini hobby projects by the students. He developed the system documentation of the entire departments & that of the college. Under industry-institute interaction, he conducted a number of industry oriented courses like CADD course, ANSYS course, Oracle course, Infosys campus connect courses (18 batches rolled out in HKBKCE), Software testing, etc. His special areas of interest are Control systems, DSP, AI, IP, Robotics, Signals & systems, Smart Intelligent Structures, Vibration control, Instrumentation, Circuits & Networks, Matlab, etc……

Mr. Arun Kumar G (B.E., M.E., (Ph.D.), MISTE, IETE, IAENG) was born in Davanagere, Karnataka, India on Oct. 15th, 1981 & received the B.E. Degree (Bachelor of Engg.) from STJ Institute of Technology, Ranebennur in Karnataka in the year 2004, M.Tech. degree in Digital Communication & Networking from the prestigious UBDT College of Engg., Davanagere in the year 2008 and Pursuing Ph.D. in Electronics in Visvesvaraya Technological University, Belgaum as a research scholar in VTU in the department of ECE. He has got a teaching & administrative experience of more than 8 years in engineering colleges in Karnataka. He has written a number of notes in various subjects as Basic Electronics, AEC, Power Electronics, Communications & his notes are widely famous all over the country. He has attended a number of certificate courses, workshops, FDPs, Symposiums, etc. He has published more than 2 dozen papers in various subjects of engineering field. His current areas of interest are control systems, power electronics, basic electronics, micro-controllers, embedded systems, communications etc….