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FRACTIONAL CONTROL SYSTEM AND ITS EMERGENCE: AN ANALYSIS THROUGH PATENT AND NON-PATENT LITERATURE

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ABSTRACT

Presently, there is requirement for more accurate, precisioned and stable control systems. Use of fractional calculus in fractional order control system (FCS) enhances the performance of the system. In this paper, an attempt has been made to have an overview of the history, evolution of fractional control systems and to establish a relationship with IPR. In a nutshell, an attempt has been made through this research paper to fill the gap of FCS & patent law and thus creating a symbiotic linkage between the two. A comparative analysis of FCS has been done with respect to its emergence and patenting trend between Indian and foreign inventors etc. considering patent literatures (PLs) and non-patent literatures (NPLs) as the source of research. It is observed that non patenting activities are prevailing in India whereas patenting activity is more in China. This may be due to easy patent protection system in China that includes utility patent also

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I. INTRODUCTION

It is observed that non-Integer systems are also known as fractional order systems (FOS). "Fractional calculus" is used to model the dynamic systems more accurately, which can be defined as the generalization of conventional calculus to orders of integration and differentiation not necessarily integer.[1] Report indicates that four situations are noticed in closed loop control systems and they are: (i) integer order (IO) plant with IO controller (ii) IO plant with fractional order (FO) controller (iii) FO plant with IO controller and (iv) FO plant with FO controller.[2]

It is reported that the control industry is dominated by IO-PID controller since long[3], but considering the matured practical use of FO-PID; it is believed that the later will gain increasing impact and wider acceptance. Some real world examples, prove that fractional order control is ubiquitous when the dynamic system is based on distributed parameters.[4] The real dynamic systems in the culture of industrial instrumentation are better characterized using a non-integer or fractional order dynamic model based on fractional calculus or, differentiation or integration of non-integer order.[5] Iso-damping property of Non-Integer or Fractional order controller fulfills the need of accuracy level in certain dynamic systems. Large number of patent applications filed by the researchers in the aforesaid field from different countries as compared to Indian context signify their awareness of protecting the same via patenting. The objective of this paper is to find out the emerging patenting trend in "Fractional order Control Systems" with respect to different fields in different countries focusing mainly on Indian framework. An attempt will be made to do a comparative analysis on the publication and patenting trend of FCS between India and other foreign countries by collecting patent and non-patent literatures.[6]

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[1] C.A. Monje, Y.Q. Chen, B.M. Vinagre, D. Xue, V. Feliu, Fractional order Systems and Controls, Springer- Verlag, London, 2010.

[2] Y.Q. Chen, I. Petráš, D. Xue, Fractional Order Control - A Tutorial, American Control Conference, pp. 1397-1411, 2009.

[3] Zak, Stanislaw H., Systems and control. New York: Oxford University Press, 2003.

[4] Yang Quan Chen, Ubiqutous Fractional Order Controls, Centre for Self-organizing & Intelligent Systems, Department of Electrical & Computer Engineering, Utah State University, Utah, USA.

[5] D. Xue, Y.Q. Chen, A Comparative Introduction of Four Fractional Order Controllers, Proceedings of the 4th World Congress on Intelligent Control and Automation, Shanghai, P.R. China, pp. 3228-3235, 2002.

[6] https://patents.google.com/(accessed 25 March 2018);Levine W.S., The Control Handbook: Control System Applications, second ed.,2010.

II. EVOLUTION OF FRACTIONAL ORDER CONTROL SYSTEMS

The mathematical phenomena, popularly called "Fractional Calculus" describes a real object more accurately than the classical "integer-order" methods.[7] A typical example of a non-integer (fractional) order system is the voltage-current relation of a semi-infinite loss transmission line or diffusion of the heat through a semi-infinite solid, where heat flow is equal to the half-derivative of the temperature. Fractional calculus is a field of mathematics study that grows out of the traditional definitions of calculus integral and derivative operators in much the same way fractional exponents is an outgrowth of exponents with integer value [. The concept of fractional calculus (fractional derivatives and fractional integral) is not new. Even, in 1695 L'Hospital asked the question as to the meaning of if n = ½; that is " what if n is fractional?". Leibniz replied that" will be equal to x". It is generally known that integer-order derivatives and integrals have clear physical and geometric interpretations. Since the appearance of the idea of differentiation and integration of arbitrary (not necessary integer) order there was not any acceptable geometric and physical interpretation of these operations for more than 300 years. It is shown that geometric interpretation of fractional integration is " 'Shadows on the walls"' and its Physical interpretation is "'Shadows of the past".[8] In the last years it has found to be used in studies of visco-elastic materials, as well as in many fields of science and engineering including fluid flow, rheology, diffusive transport, electrical networks, electromagnetic theory and probability. In the last decades of the last century there has been continuing growth of the applications of fractional calculus mainly promoted by the engineering applications in the fields of feedback control, systems theory, and signals processing. Recent findings support the notion that fractional-order calculus should be employed where more accurate modeling and robust control are concerned. Specifically, fractional order calculus found its way into complex mathematical and physical problems. In general, fractional-order calculus may be useful when modeling any system which has memory and/or hereditary properties.[9] In the field of automatic

[7]Levine W.S., The Control Handbook: Control System Applications, second ed.,2010. Katsuhiko Ogata, System Dynamics, fourth ed., Prentice-Hall, New Jersy,2002

[8] Igor Podlubny, Geometric and Physical Interpretation of Fractional Integration and Fractional Differentiation, Department of Informatics and Control Engineering, Technical University of Kosice, Slovak Republic,2008.

[9] Shantanu Das, Functional Fractional Calculus for System Identification and Controls, Library of Congress Control Number: 2007934030, ISBN 978-3-540-72702-6 Springer, Berlin Heidelberg New York,2007.

control, fractional calculus is used to obtain more accurate models, develop new control strategies and enhance the characteristics of control systems. Several toolboxes have been developed for this particular set of tasks. Among them are MATLAB toolboxes CRONE [12], developed by the CRONE team, NINTEGER , developed by Duarte Valério[13] and FOMCON developed by Dr. Aleksei Tepljakov[14]. Evolution can be categorized as per the need or as per the philosophy which is described briefly in the following sub sections.

Need Based Evolution

Real objects in nature are generally fractional and hence Fractional calculus can more accurately describe them. Traditional calculus is a particular case of Fractional calculus [2]. The main reason for using the integer-order models was the absence of solution methods for fractional differential, integral equations. It can be used in control theory, capacitor theory, and circuit.

Philosophy based Evolution

The basic control actions in the frequency domain are mainly proportional, derivative, and integral, and their main effects over the controlled system behaviour are: to increase the speed of the response, and to decrease the steady-state error and relative stability [1]. The aforesaid controller is less sensitive to changes of parameters of the control system and this is due to the two extra DOF to better adjust the dynamical properties of a fractional order control system. Hence, fractional order control philosophy weighs more than the integer order control as per its increasing demand in practical applications.

III. EVOLUTION OF FRACTIONAL CONTROL

Figure 1 depicts a graphical view of the timeline of different scientists in the fractional domain, starting from Newton. It is observed that fractional calculus is used even in 1650.

1650-1700		
Isaac Newton(1643-1727)	Gottfried Leibnibtz(1646-1716)	L. Hopital(1661-1704)

1700-1750		
L. Euler(1707-1783)	Lagrange(1736-1813)	Laplace(1749-1827)

1750-1800
Fourier(1768-1830)

1800-1850						
Abel (1802-1829)	Liouville (1809-1882)	Weierstrass (1815-1897)	Riemann (1826-1866)	Letnikov (1837-1888)	Grunwald (1838-1920)	Mittag Leffler (1846-1927)

1850-1900						
Heaviside (1850-1925)	Nekrasov (1853-1924)	Weyl (1885-1955)	Littlewood (1885-1977)	Hardy (1877-1947)	Riesz (1866-1969)	Levy (1886-1971)

1900---
William Feller(1906-1970)

Figure 1: Timeline of eminent scientists in the area of Fractional Calculus.

A. ADVANTAGES OF FRACTIONAL ORDER CONTROL SYSTEM OVER INTEGER ORDER CONTROL SYSTEM

The fundamental advantage of Fractional Order Control system is that the fractional-order integrator weights history using a function that decays with a power-law tail. The effect is that the effects of all time are computed for each iteration of the control algorithm. This creates a 'distribution of time constants,' the upshot of which is there is no particular time constant for the system.[10]

The fractional integral operator is different from any integer-order rational transfer function, in the sense that it is a non-local operator that possesses an infinite memory and takes into account the whole history of its input signal.[11]

Fractional-order control shows promise in many controlled environments suffering from the classical problems of overshoot and resonance. Fractional-order control is capable of suppressing chaotic behaviors in mathematical models like muscular blood vessels.[12]

[10] M. S. Tavazoei, M. Haeri, S. Bolouki, and M. Siami, Stability preservation analysis for frequency-based methods in numerical simulation of fractional-order systems, SIAM Journal on Numerical Analysis, vol. 47, pp. 321–338, 2008

[11] M A Rahimian and M S Tavazoei; Stabilizing fractional-order PI and PD controllers: an integer-order implemented system approach , JSCE1043 Proc. IMechE Vol. 224 Part I: J. Systems and Control Engineering.

[12] Aghababa, Mohammad Pourmahmood; Borjkhani, Mehdi. Chaotic fractional-order model for muscular blood vessel and its control via fractional control scheme". Complexity. *20 (2): 37–46.*

B. ADVANTAGES OF FRACTIONAL ORDER PID CONTROLLER OVER INTEGER ORDER PID CONTROLLER

We can analyze specifically the advantages of FOPID controllers over the classical or IOPID controllers as:

- In fractional order PIDs we have 5 parameters unlike 3 in conventional PIDs. Hence, we have more parameters to tune which will lead to better accuracy.[13]
- Implementation of conventional PIDs requires one invariable pole and 2 zeros whereas several poles and zeros are required in fractional PIDs[14]
- In fractional order PID controller, step responses have roughly constant overshoots even when the gain of the plant varies.[15]
- A Fractional order PID controller enhances the control performance compared to integer or conventional PID controller[16]
- It is less sensitive to changes of parameters of the control system and this is due to the two extra DOF to better adjust the dynamical properties of a fractional order control system.[17]
- Tuned fractional order PIDs perform better than the tuned PID as the former are more flexible .
- For the derivative action, introduction of $\pi/2$ phase lead in the frequency domain increases the relative stability whereas sensitivity is increased with the increase of gain having a slope of 20dB/dec.
- When integral action is considered, the introduction of $\pi/2$ phase lag decreases relative stability and infinite gain at zero frequency eliminates steady-state errors

[13] S. Debbarma, L.C. Saikia, N. Sinha, Automatic generation control using two degree of freedom fractional order PID controller, Int. J. Elec. Power Energ. Syst. 58 (2014) 120–129.

[14] Duarte Valerio, Jose Sa da Costa, Tuning-Rules for Fractional PID Controllers, IFAC Proceedings Volumes,Vol.-39, January 2006.

[15] M A Rahimian and M S Tavazoei; Stabilizing fractional-order PI and PD controllers: an integer-order implemented system approach , JSCE1043 Proc. IMechE Vol. 224 Part I: J. Systems and Control Engineering.

[16] Duarte Valerio, Jose Sa da Costa, Tuning-Rules for Fractional PID Controllers, IFAC Proceedings Volumes,Vol.-39,January 2006.

[17] S. Debbarma, L.C. Saikia, N. Sinha, Automatic generation control using two degree of freedom fractional order PID controller, Int. J. Elec. Power Energ. Syst. 58 (2014) 120–129.

- Frequency domain experiments are more preferred in different fields such as electrochemistry, material science etc. having memory phenomena to obtain equivalent electrical circuits for correct reflection of the dynamic behavior of the system.
- The aforesaid fields use lumped elements such as resistors, inductors, and capacitors and hence some unexpected behaviors may be the outcome.
- Fractional operators arise in a natural way in the frequency domain which can be observed by the use of standard definitions of repeated integrals and derivatives.

A. FRACTIONAL CONTROL SYSTEM & PATENTING

FCS being an emerging advanced technological field. Inventions in this field demands protection in the form of IPR to reward inventor and or author. One of the main functions of the patent system is to foster technological innovation by providing an incentive for research and development. The patent system also works to disseminate technical information and promote technology transfer by decreasing transaction cost. Patenting of FCS will undoubtedly promote more innovations in the specific fields such as robotics, bio-medical and aerospace engineering. These are the areas which need accuracy and robustness at exact dimensions, not attained by the classical control system generally.

IV. FRACTIONAL ORDER SYSTEMS & CONTROL: LITERATURES BY INDIAN AND FOREIGN AUTHORS

A. NPLS & PLS BY INDIAN AUTHORS

NON-PATENT LITERATURES BY INDIAN AUTHORS

Figure 2 shows no. of non-patent literatures by Indian authors in the last 8 years. It is observed that the maximum number. Of research papers published in the year 2017. This indicates that FCS field has been progressing over the years.

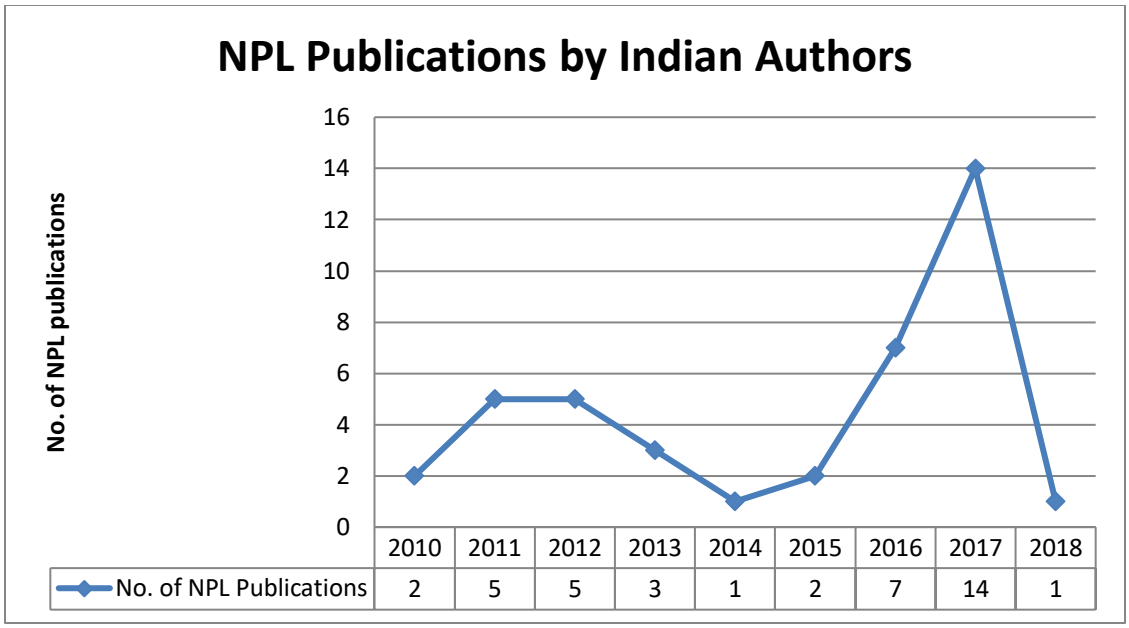

Figure 2: NPL [Non Patent Literature] publications by Indian Authors in last 8 years.

Figure 3 illustrates that control engineering plays vital role in having more than 50% of literatures, some other application fields such as "Nuclear Engineering", "Computer & Electronics Engineering" etc. are making their presence felt.

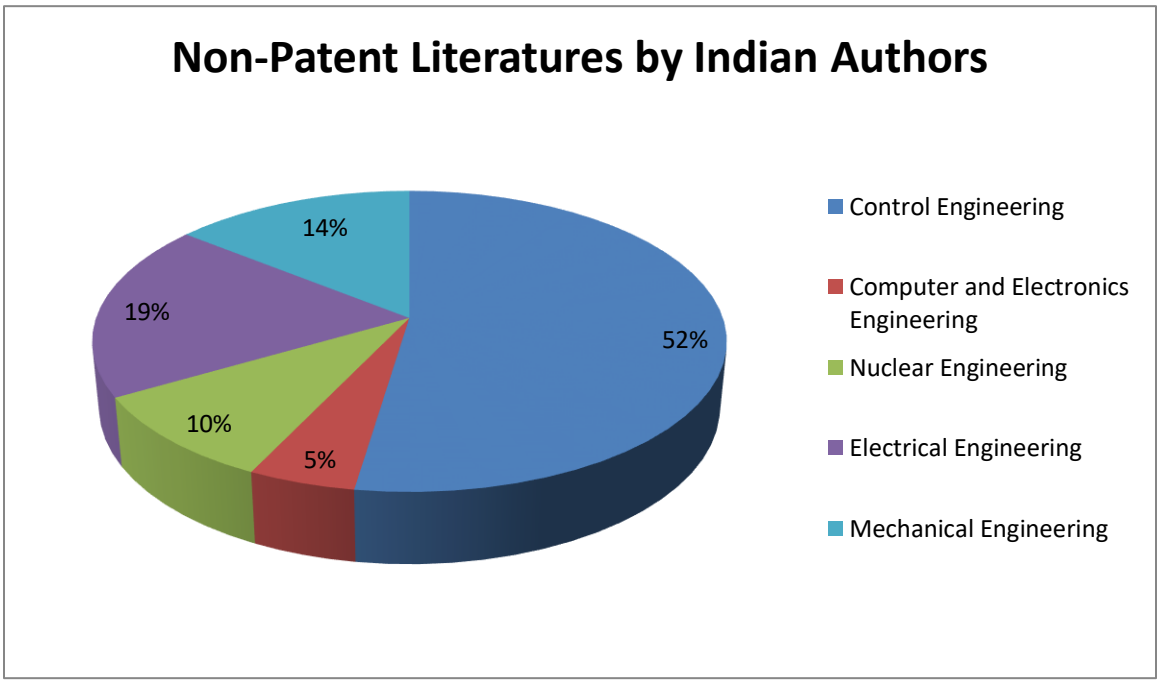

Figure 3: NPLs on fractional order concept by Indian Authors in different fields.

1. PATENT LITERATURES BY INDIAN INVENTORS

Figure 4 shows the no. of patent literatures by Indian inventors in the last 8 years shows that year 2018 has secured the top position by attaining maximum no. of publications on application of FOS and FCS in various fields.

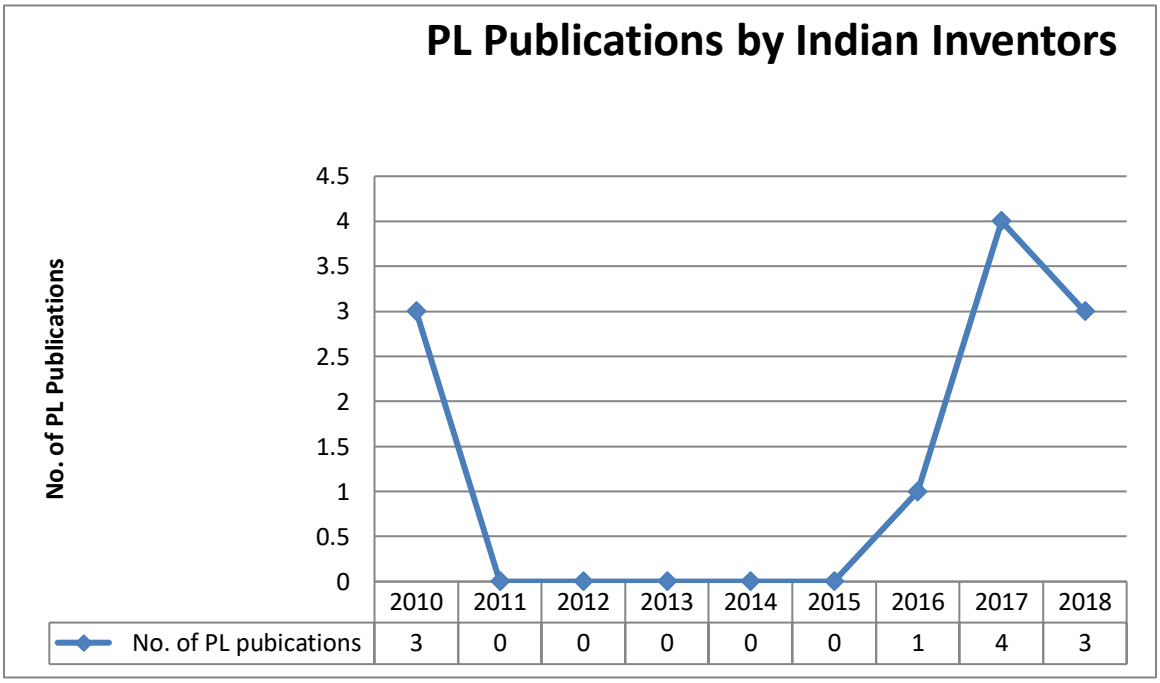

Figure 4: PL publications by Indian Inventors in last 8 years

Figure 5 illustrates that Indian inventors have tried to implement FOS and FCS in various fields which is a welcoming step. Though Electrical Engineering acquires the top position in patent filing it is seen that some of them are abandoned. The statistics of NPLs and PLs reflects the fact that some authors are not applying for patents at all. This shows that though the research is in full swing, due to some or the other factors the no. of granted patents is almost nil.

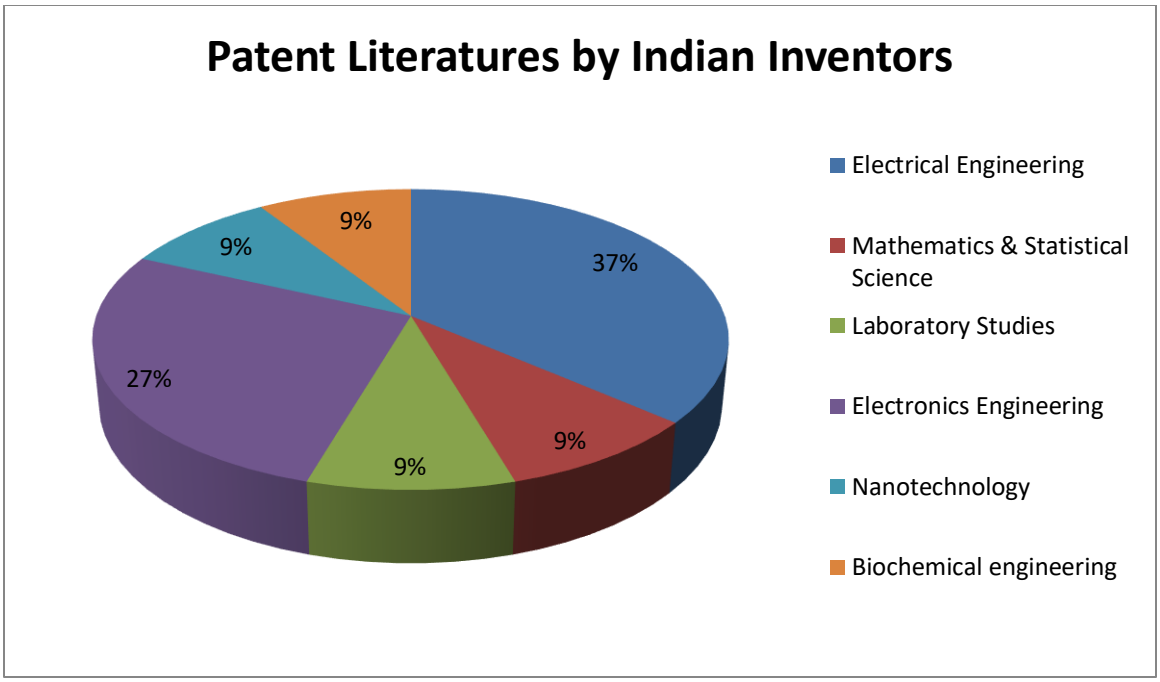

Figure 5: PLs on fractional order concept by Indian Inventors in different fields.

B. NPLS & PLS BY FOREIGN AUTHORS

1. NON-PATENT LITERATURE (NPL) BY FOREIGN AUTHORS

Figure 6 illustrates NPL by foreign authors. It is observed that that "Robotics" and "Control Engineering" have occupied almost 60% out of other various fields. Some applications are also found in rare fields such as "Astronautics" & "Aerospace" etc. This shows the interest of the authors in implementing FCS, FOS in different fields worldwide. Hence, the trend of research is same as in India.

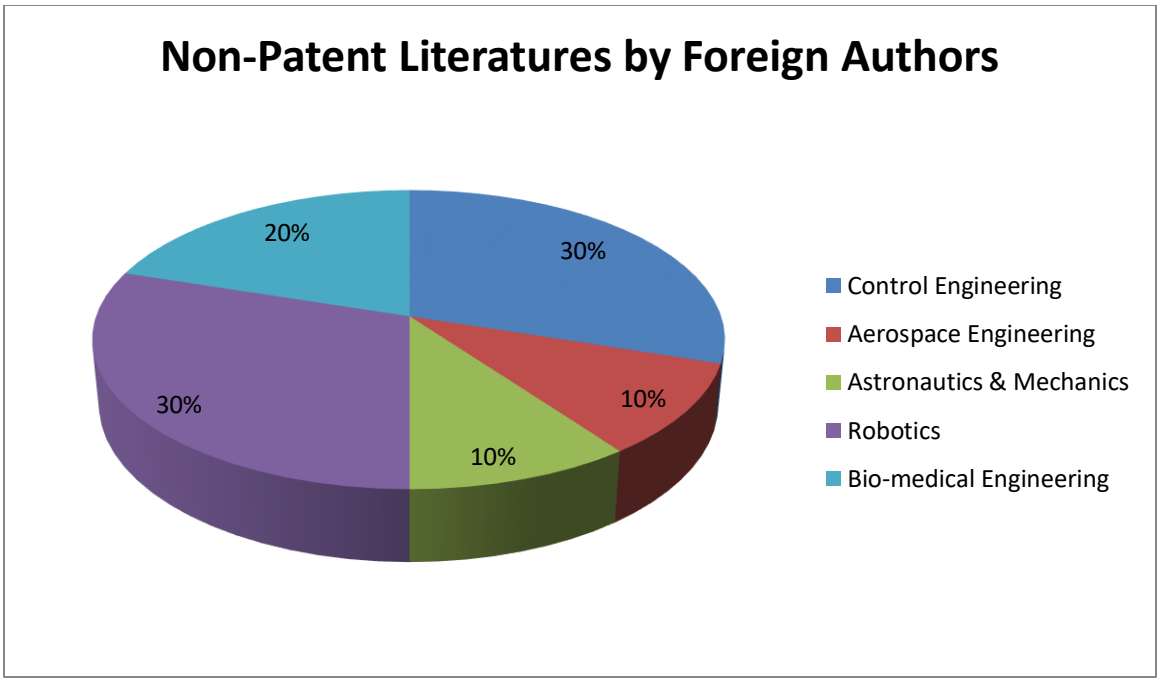

Figure 6: NPLs on fractional order concept by Indian Authors in different fields.

2. PATENT LITERATURE BY FOREIGN INVENTORS

Figure 7 illustrates that up to year 2010, China was in the nascent stage in terms of published or granted patents in the respective field. The duration 2011-2015 and 2016-2018 clearly shows the up rise of China in terms of filing, publishing and granting of patents. This shows the unique combination of their hard work, right attitude towards research and proper implementation of IP law.

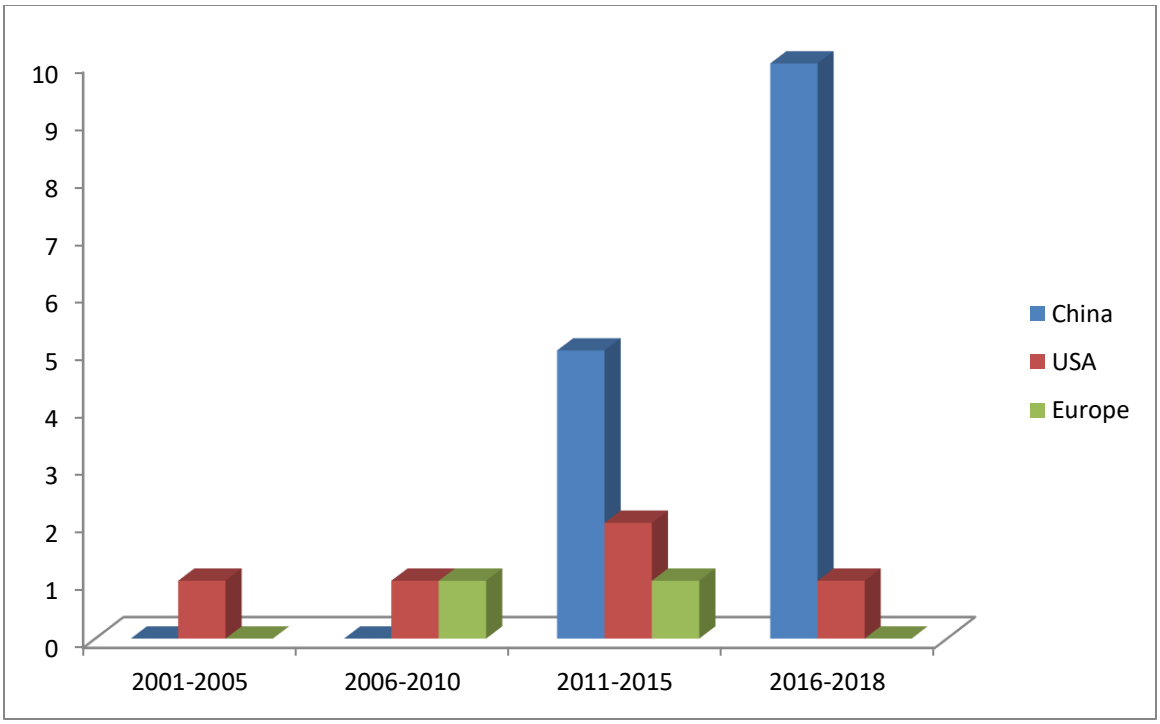

Figure 7: No. of patents per country in the duration 2000-2018.

It is observed that China is dominating in this field. Let us discuss a brief of Chinese patent law.

1. Registration process[18]

In case of no formality objections, lack of substantive examinations lead to the registration of a utility model patent which is granted within 6-12 months. This quick file-to-grant cycle makes the easy and quick entry of the new products in the market.

2. Short Life Inventions [19]

Short life products are well protected via utility model patents. These are particularly well suited for protecting the improvements of existing products which normally don't satisfy the requirements for obtaining an invention patent.

3. Dual-filing system[20]

[18] K.S. Miller, B.Ross, An Introduction to the Fractional Calculus and Fractional Differential Equations, John Wiley and Sons, Newyork,1993.

[19] https://www.deacons.com.hk/news-and-insights/publications/10-advantages-of-chinese-utility-model-patents.html (accessed 8 September 2018).

Simultaneous application of an invention patent and a utility model patent are possible for the same subject matter. The patent owner can enjoy the benefits of the fast issuance of the utility model patent, as well as the advantage of the longer term protection of the invention patent.

Besides the above significant factors some other advantageous factors are “Less requirement for inventive step”, ”Cheaper compared to invention patent applications”, ”Prompt enforcement”, ”Enforcement venue options”, effectiveness etc.

Figure 8 shows the patent literatures from foreign inventors.

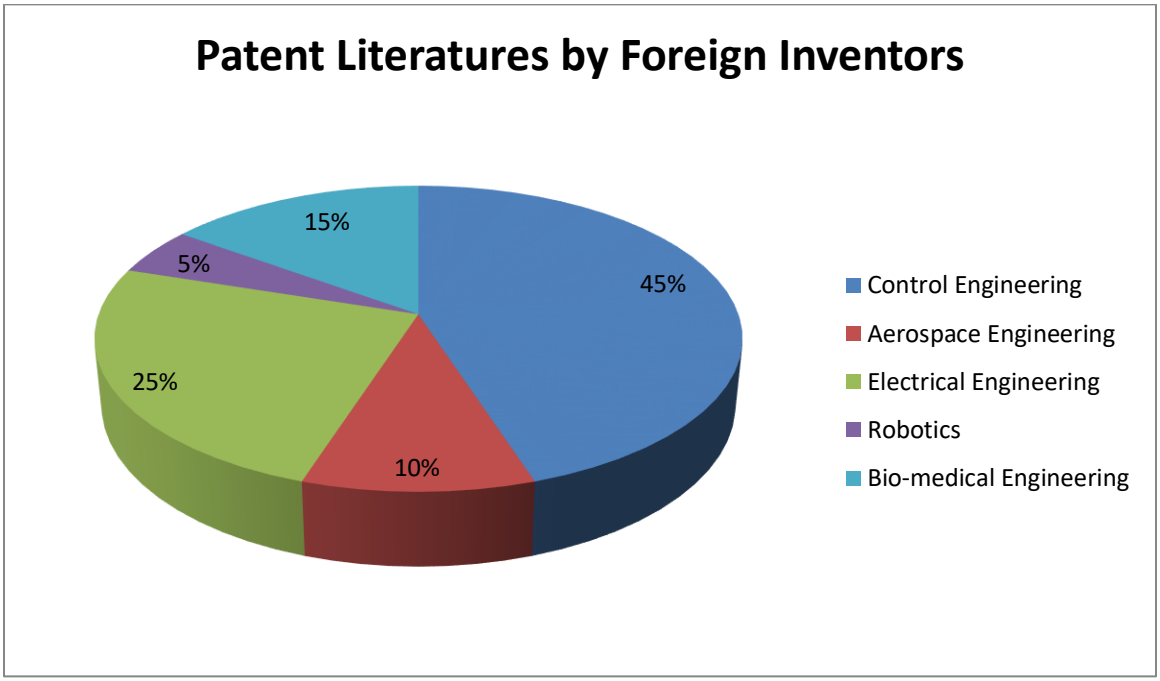

Figure 8: Patent literature (PLs) on fractional order concept by Foreign Inventors in different fields.

From figure 8, it is very much clear that foreign inventors have been filing patent on use of fractional order. They have reached almost all the significant fields of science and engineering in terms of applying and protecting fractional order concept. “Control Engineering” secures the top most position among all other fields. It is observed that maximum patents are in granted status.

[20] https://www.deacons.com.hk/news-and-insights/publications/10-advantages-of-chinese-utility-model-patents.html (accessed 8 September 2018).

V. OBSERVATION AND CONCLUSION

It is observed that the rate of filing of patents in India is very less as compared to other foreign countries, discussed in this paper. The search statistics indicates a remarkable degree of difference in the no. of patent literatures and non-patent literatures by Indian authors. This may create an alarming situation for the IP protection of scientific and engineering researches.Section-3(k) of The Indian Patent Act,1970 says "*a mathematical or business method or a computer program per se or algorithms are not patentable*". As most of the Indian NPLs are based on mathematical methods, computer programs or algorithms and section-3(k) denies them to be patented, this may provide a reason to the remarkable difference between PLs and NPLs. It is also observed that some inventions are published and patented by the same inventor which reflects the fact that patenting has not prevented him/her from publishing the literature. Statuses of some of the applied patents in India are found abandoned as well. This may be due to various hindrances such as funding, commercialization issues etc. The search analysis of other countries illustrate that China has become a global figure in the IP protection of FCS surmounting USA as well. Despite of all the discouraging statistics, a ray of hope lies in the form of non-patent literatures, which indicates the ardent interest of the Indian researchers in the specific field. Areas like control engineering, mechanical engineering and electrical engineering are more explored as the application fields of FOS and FCS by the Indian authors.