Omnipresence of Tesla's Work and Ideas

Miloš D. Ercegovac

***Abstract*— Tesla made several of the most significant discoveries in electric power systems and wireless signal transmission. These contributions were crucial in enabling economic and technological progress leading to our modern world. In his long creative life, he impacted many other areas in engineering, sciences, medicine, and art. This paper discusses examples of Tesla's work as it influenced others in diverse areas over a long period of time, continuing to the present day.**

***Index Terms*— lighting, mental models, microfluidics, neuroimaging, resonant circuits, sensors, telerobotics, thermomagnetic generators, transducers, turbines, visualization.**

I. Introduction

THIS paper discusses several examples of the continuing presence of Tesla's work in science, engineering, and other areas. We analyze papers and patents over an extensive period of time that cite directly Tesla's work and comment on his ideas. It is evident that the impact of some of his creations is still present in several research and industrial areas, attesting their timeless ingenuity, depth and uniqueness – after almost a century since their inception.

Tesla's pioneering discoveries and inventions in electric power systems and wireless signal transmission are evidently among the most significant creations that enabled the economic and technological progress of society. These will not be discussed here. Many of his other engineering achievements – he seemed to have an unbounded wealth of ideas – such as wireless lighting, uses for high frequency currents, wireless remote control, bladeless turbine, and valves with no moving parts, as well as visionary ideas about future developments such as radar, facsimile, and wirelessly interconnected world, left a notable impact on modern research and development.

Brentano offerred the following characterization of Tesla [1], *"There are three aspects of Tesla's work which particularly deserve our admiration: The importance of the achievements in themselves, as judged by their practical bearing; the logical clearness and purity of thought, with which the arguments are pursued and new results obtained; the vision and the inspiration, I should almost say the courage, of seeing remote things far ahead and so opening up new avenues to mankind ."*

To analyze the impact of Tesla's work in general is a daunting research task. The comments presented here are an attempt to illuminate only a small portion of it in order to show the continuing omnipresence of Tesla's work and ideas. In the following sections we discuss several areas ranging from mental models and visualization in problem solving to tele-robotics, including areas such as radio-frequency (RF) lighting, sensors, microfluidics, and performing art.

The author's affiliation: Computer Science Department, University of California at Los Angeles, 4731H Boelter Hall, UCLA, Los Angeles, CA 90095-1596, USA. E-mail: milos@cs.ucla.edu

II. Mental Models, Visualization, and Creative Process

Tesla's way of visualizing problems and discovering solutions in his mind before committing time and effort to the physical realization anticipates amazingly well the modern approach of using computer-based visualization in discovery, creation and exploration of solutions to complex problems in science and engineering. Without it, progress in many vital areas such as molecular biology, design of aircraft and complex mechanical systems, would be hampered or impossible. West [33], [32] gives a fascinating account of exceptionally creative people including Faraday, Tesla, Poincaré, and da Vinci who had the ability to visualize solutions to a desired level of perfection. West develops a convincing argument about the power of learning in "one's mind" with the help of ever more powerful computer-based visualization systems.

West uses Tesla as a good example of an inventor who relied on "a powerful innate ability to develop mental models as a tool to produce what might be called prototypes in thought." Tesla was fully aware of his powerful and unusual method of work [23] which enabled him to create an extensive number of profound inventions:

" ... I observed to my delight that I could visualize with the greatest facility. I needed no models, no drawings or experiments. I could picture them all in my mind."

Then he elaborates on his *"new method of materializing inventive concepts and ideas, which is radically opposite to the purely experimental ... . The moment one constructs a device to carry into practice a crude idea he finds himself unavoidably engrossed with the details and defects of the apparatus . . . . My method is different. I do not rush into actual work. When I get an idea I start at once building it up in my imagination . . . . In this way I am able to rapidly develop and perfect a conception without touching anything. When I have gone so far to embody in the invention every possible improvement I can think of and see no fault anywhere, I put into concrete form this final product of my brain. Invariably my device works as I conceived that it should..."*

West comments *"It is of no small significance that what Tesla could do in his own mind, without the help of outside machines, is just what is now recommended by consultants investigating the successful use of interactive computer-aidded design and other three dimensional graphics computing systems: The speed and power of 3D computing has all but eliminated the requirements to produce physical prototypes and models."*

The use of modern 3D visualization systems allows management and engineering design of increasingly complex systems in aerospace industry, biology research and drug development, and architecture - to name a few. West suggests that *"It is* *possible, therefore, that in such a new world of education, research and work, advanced interactive computer systems may have profound but sometimes unexpected beneficial effects. If (like Einstein) one's intuition is clear enough, or, if (like Tesla) one's mental model is powerful enough, then one might be able to dispense with direct physical experiment for a time and do a great deal of experimenting and simulation of reality using the imagination alone. Then, hopefully, the tests and confirmations can be performed much later in the process, through real experimentation, with more unequivocal results."*

III. Tele-presence and Wireless-Radio Controlled Systems

One of the most futuristic inventions was Tesla's radio-controlled boat [23], described in U.S. Patent 613,089 (1898). Tesla effectively introduced tele-robotics and foresaw its potential when he articulated a modern Artificial Intelligence view of robotics: *[it] will be able to follow a course laid out or obey commands given far in advance, it will be capable between what it ought and what it ought not to do and of recording impressions which will definitely affect its subsequent actions.* Paulos and Canny [18] discuss the progress in systems providing tele-presence, i.e., the systems which allow user to "move" into a remote space and act in it as being physically present. Tesla's rather complete design of a wireless-radio controlled boat anticipated tele-operated systems developed 50 years later for use in hostile environments.

IV. Radio-Frequency (RF) Lighting

Electric lighting sources have been a target of intense engineering efforts during almost two centuries. The early work culminated in Edison's incandescent bulb which has evolved over the years into the most common electrical device. Its inefficiency and short life time, however, motivated search for better lighting sources, eventually leading to radio-frequency, electrode-less lighting devices. Godyak [7] observes that the first proposal for RF electrode-less lighting appeared about a century years ago in the 1891 lecture [20] delivered by Tesla before the American Institute of Electrical Engineers at Columbia College, New York, in which Tesla demonstrated a "wireless light", energized by a capacitive RF discharge. Tesla's wireless lamp embodied the key concept which led to modern lighting remotely energized by microwave electromagnetic fields. In particular, a microwave-driven high intensity discharge (HID) sulfur lamp described in [30] appears as a practical realization of Tesla's idea. This lamp, shown in Figure 1, is remotely energized by a microwave power source generated by a magnetron. A quartz bulb filled with argon and sulfur, is rotated in the microwave resonant cavity, covered with a light transparent window. It has a very high efficiency of about 100 lm/W with an expected life of 15,000 hours. In fact, it illuminates the National Air and Space Museum in Washington, DC.

RF light sources required recent progress in semiconductor power switching electronics and advancements in RF plasma understanding to become commercially acceptable. However,

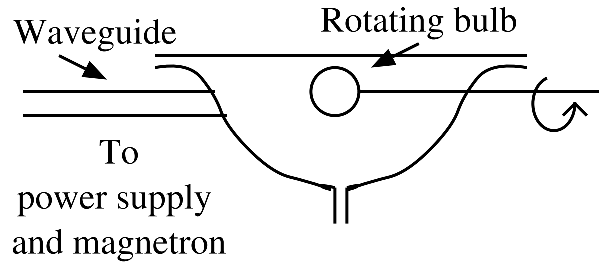

Fig. 1. Microwave-powered sulphur lamp realizing Tesla's proposed wireless light (From [7]).

these advances were not available during Tesla's time, nevertheless his basic idea of wireless light survived the test of time.

V. Sensors and Transducers

In a survey paper [14] that focuses on a finger-like (inter-digital) geometric structure of electrodes that are frequently encountered in a variety of sensor and transducer designs, Tesla's 1891 patent in [22] is discussed as possibly the earliest example of interdigital electrode design (Figure 2). The use of interdigital electrodes became pervasive in areas such as micromechanical systems (MEMS), chemical sensing, piezoacoustics, and biotechnology.

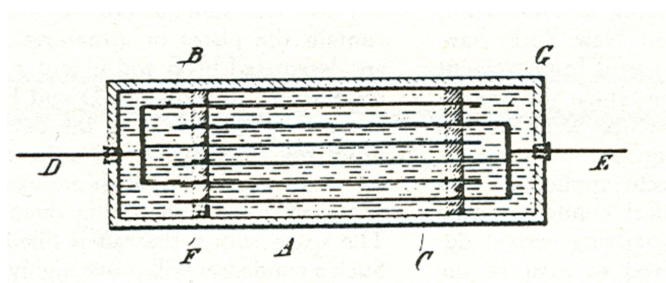

Fig. 2. Tesla's condenser design with interdigital plates. (From [22])

The term interdigital refers to a fingerlike pattern of parallel in-plane electrodes providing a capacitance of the electric fields used by sensors, increasing approximately linearly with the number of plate electrodes. In Tesla's invention each finger electrode is a rectangular plate, immersed in an insulating liquid. The same principle is sometimes used in the design of modern capacitors. Periodic interdigital patterns are also used in the design of strip antennas. An example of a modern sensor-transducer design with interleaved electrodes is illustrated in Figure 3.

VI. Bladeless Turbines

In 1909 Tesla proposed a novel design of turbines made of several closely spaced rotor disks (U.S. Patents No. 1,061,142 and 1,061,206) . These turbines are commonly referred to as Tesla turbines and, sometimes, as bladeless turbines. Their unique principle continues to be a starting point for many new designs currently proposed. For example, in the 2004 U.S.

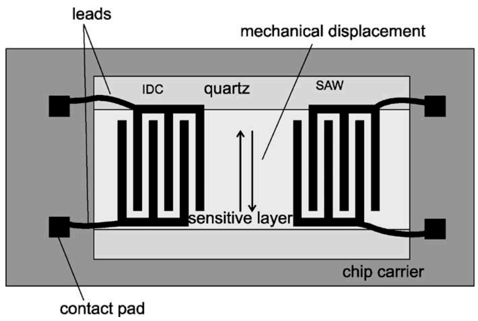

Fig. 3. An example of modern sensor - transducer design. (From [14], [13])

Patent No. 6,682,077 (Labyrinth Seal for Disc Turbine) which improves on Tesla's turbine by introducing an improved seal to reduce fluid turbulence. The author states that "Tesla's design offers substantially similar gaps between pairs of opposed surfaces." In other words, Tesla's original engineering details are fundamental and remained relevant for current designs.

Tesla's turbine is of growing interest in the design of medical devices. In [15] a multiple disk centrifugal pump (MDCP), based on the Tesla turbine design [25], is being developed as a potential left ventricular assist device. A schematic drawing of the pump is shown in Figure 4.

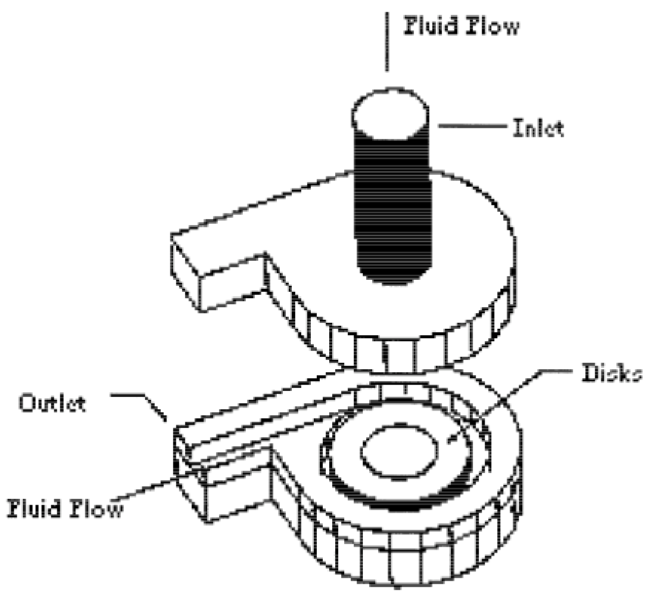

Fig. 4. Multi-disk blood pump. (From [15]).

Tesla's bladeless pump is essential in an assist device under steady or pulsatile flow. Other advantages include far more stable flow regimes than those of other centrifugal blood pumps and, importantly, its construction is less complex compared to other centrifugal blood pumps.

VII. Micropumps with fixed valves

Traditional methods of controlling fluid flow with valves using moving parts are imperfect due to mechanical wear of moving parts, and poor behavior for rapid flow impulses and when the fluid is highly heated or corrosive. Pumps with valves having no moving parts (fixed valves) are of interest because they avoid the above mentioned problems and are relatively easy to fabricate and inherently reliable due to their simplicity [17], [31]. The original, rather ingenious idea of such a valve with no moving parts and its design are described in Tesla's 1920 US Patent No. 1,329,559. It is an ingenious device that acts as a fluid diode. The resistance in a non-conduction direction can be arbitrarily increased by adding identical sections. Figures 5 and 6 illustrate the original invention and its model as used in a recent work [17], respectively. A realization of a micro pump using Tesla's valve is shown in Figure 7.

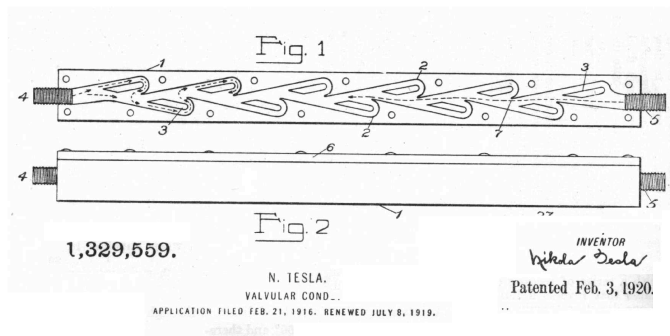

Fig. 5. Valve without moving parts. (From US Patent 1,329, 559, (1920)).

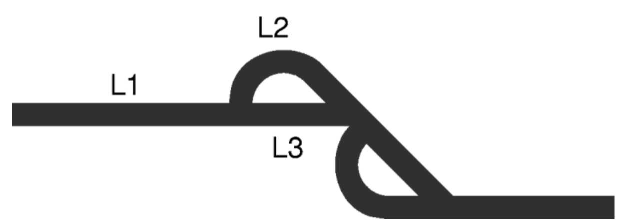

Fig. 6. A model of a typical Tesla-type valve. (From [17])

The use of Tesla-type valves in micropumps, which are key components in microfluidic systems, is of growing interest [17]. These systems are an important area of MEMS, with many applications such as drug delivery, microbiology, and clinical analysis in medicine.

VIII. Thermomagnetic Generators

A thermomagnetic generator converts heat energy into electrical energy. The generator consists of a permanent magnet, a shunt made of ferromagnetic material, a pickup coil, and a heat source and sink. Tesla proposes one of the early design in U.S. patent 428, 057 (Pyromagneto-Electric Generator), 1890. A general diagram of a thermomagnetic-electric generator is shown in Figure 8. Tesla's invention is depicted in Figure 9. Elliott [3] discusses improvements of effciency of thermo-electric generators based on gadolinium which allows heat source to be at the room temperature of 20^{o}C. Kuzmin [11] reviews results of experimental and theoretical investigations of the magnetocaloric effect (MCE) and mentions ongoing efforts using this effect to create magnetic cooling devices.

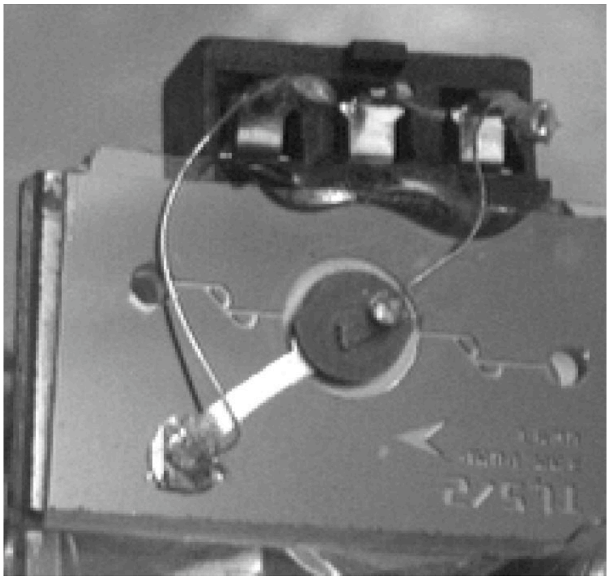

Fig. 7. Fixed-valve micropump with a 3 mm diameter chamber and 114 m wide channels. The channels operate as valves, providing a higher pressure drop in the reverse (left-to-right) than in the forward direction. (From [17])

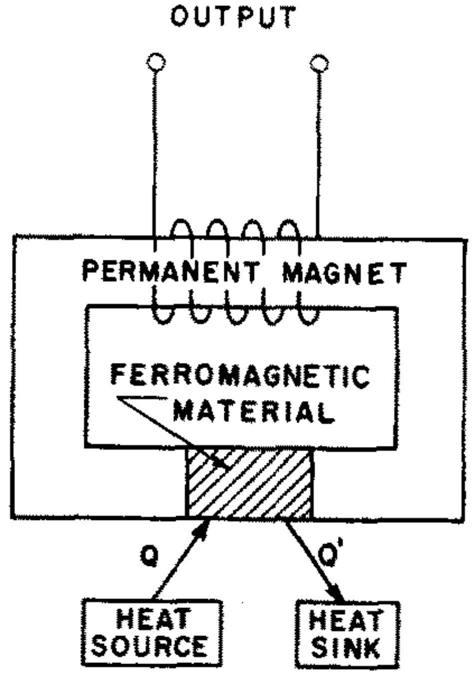

Fig. 8. A thermomagnetic-electric generator .(From [3])

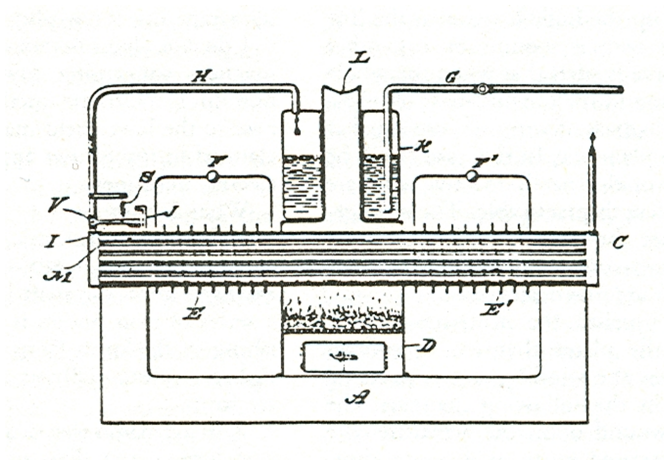

Fig. 9. Tesla's pyromagneto-electric generator .(From [24])

IX. Electric Guns

Realizing a science-fiction idea of electric guns has been an ongoing research effort since World War II with potentially significant implications on warfare – an activity humans seem not be capable of being without. One approach of powering electric guns uses special generators of a homopolar (unipolar) type, called HPGs [16]. This article identifies Tesla's work in this area as one of the earliest designs of homopolar generators [21]. Tesla's primary interest was in field self-excitation in homopolars and he proposed several ways of achieving this, such as spirally subdividing the rotor disk or drum to direct the current flow appropriately. His objective was to achieve a simple machine in which the usual field coils and poles may be omitted and the machine may be made to consist only of a cylinder or of two disks enveloped by a metal casting. Tesla designed and built several generators of that type such as *"novel two-disk HPGs in which the high-speed sliding contact was replaced by a conducting belt connecting the two disk peripheries electrically, so that brushes were only required at the low-speed shafts. "* The magnetic field was in opposite directions through the two disks, so that the machine outputs were connected in series. Tesla mentions that *"several machines with belt contact were constructed by the writer two years ago and worked satisfactorily."* Although this approach may not be applicable for operating speeds expected in modern designs, its influence on the field survived more than a century.

X. Neuroimaging

"I expect to photograph thoughts, ... In 1893...I became convinced that a definite image formed in thought must, by reflex action, produce a corresponding image on the retina, which can be read by suitable apparatus. This brought me to my system of television..." [27]. While Tesla's futuristic idea of a "brain reading device" remains largely in the realm of science fiction, there is a strong research effort in brain imaging. Significant progress is being made in the use of non-invasive neuroimaging signals to partially "decode" the mental states of a person [8]. These are strong signs that Tesla's "brain reading device will eventually become a reality.

XI. Electricity in Medicine

Tesla demonstrated a highly spectacular work on high-frequency currents in the early 1890s. His results fascinated both experts and lay people and he was invited to present his now classic paper "High frequency oscillators for electro-therapeutic and other purposes," to the American Electro-

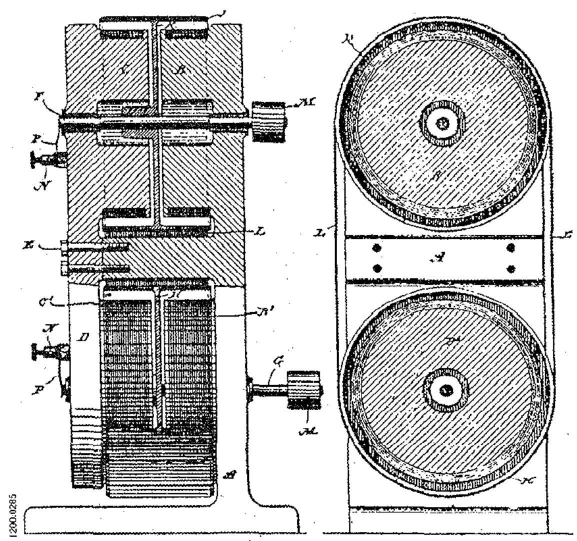

Fig. 10. Tesla's double-disk homopolar generator (From [21]).

Therapeutics Association in 1898. This points out that Tesla had a strong impact on the emergence of electrotherapeutics as a subdiscipline in medicine. Rhees [19] provides a good account of Tesla's role in electrotherapeutics. He notes that, unlike his work on polyphase systems and induction motor/generator which quickly produced far-reaching changes in power systems, he made significant contributions to induction heating and medical diathermia.

Tesla was first to recognize properties of high-frequency (HF) currents when applied to human body and he proceeded to develop a variety of devices for their generation. *"One of the early observed and remarkable features of the high frequency currents, and one which was chiefly of interest to the physician, was their apparent harmlessness which made it possible to pass relatively great amounts of electrical energy through the body of a person without causing pain or serious discomfort."*

Unlike many "experts" at that time who made outlandish and risky claims about electrical treatments, Tesla was careful not to imply that he knew how to apply HF currents in medical treatments - he left that to the physician. *"While it remained for the physician to investigate the specific actions on the organism and indicate proper methods of treatment, the various ways of applying these currents to the body of a patient suggested themselves readily to the electrician."*

Tesla, however, offered a pretty bold suggestion about maintaining personal hygiene with his approach of harmless HF currents:

"As before remarked, by adopting the method described, the body of a person may be subjected without danger to electrical pressures vastly in excess of any producible by ordinary apparatus, for they may amount to several million volts, as has been shown in actual practice. Now, when a conducting body is electrified to so high a degree, small particles, which may be adhering firmly to its surface, are torn off with violence and thrown to distances which can be only conjectured. I find that not only firmly adhering matter, as paint, for instance, is thrown off, but even the particles of the toughest metals are torn off. Such actions have been thought to be restricted to a vacuous inclosure, but with a powerful coil they occur also in the ordinary atmosphere. ... The continuous improvement of the instruments and the study of the phenomenon may shortly lead to the establishment of a novel mode of hygienic treatment which would permit an instantaneous cleaning of the skin of a person, simply by connecting the same to, or possibly, by merely placing the person in the vicinity of a source of intense electrical oscillations, this having the effect of throwing off, in a twinkle of the eye, dust or particles of any extraneous matter adhering to the body. Such a result brought about in a practicable manner would, without doubt, be of incalculable value in hygiene and would be an efficient and time-saving substitute for a water bath, and particularly appreciated by those whose contentment consists in undertaking more than they can accomplish." In view of a predicted drastic shortage of water in the coming decades, Tesla's "electrohygiene" might become an interesting alternative in personal hygiene.

Rhees [19] notes that Tesla was one of the first electrical engineers to consider the physiological effects of high-frequency currents. After discovering that he could induce rapid heating in metal bars, even melting them, Tesla speculated that living tissues also could be heated in the same manner. He also noted the unexpected fact that humans can endure high-frequency currents of extremely high voltage without apparent harm. These findings led Tesla and others to suggest that such currents might be of medical use. This approach became known as diathermy where high-frequency electrical currents are used to heat deep muscular tissues to increase blood flow, thus speeding up recovery. Diathermy is also used in surgical procedures to seal blood vessels with electrically heated probes. Two key investigators of electrophysiology during the nineteenth century were d'Arsonval and Tesla. They independently studied effects of high-frequency current on human body and discovered their physiological effects . In 1892, Tesla met d'Arsonval on a lecture tour of France: he was pleased that d'Arsonval used his oscillators to investigate the physiological effects of high frequency currents. History has not been kind to Tesla – the credit for all of the pioneering work in the field of electrotherapy has gone almost exclusively to d'Arsonval [10].

It can be noted that Tesla's work found central use in other disciplines in medicine. For example, early pioneers in oral radiology [12] like Kells used a Tesla coil as a part of equipment for taking dental radiographs. Tesla himself wrote on the negative effects of X-rays on humans [29].

XII. Electric Body and Performing Arts

Electric performances art [4] can be defined as the theatrical display of electrically manipulated human bodies. This art form started with the scientific/technological electricity innovations of the 18th century and evolved to use most advanced computer-based muscle-control pieces. Not surprisingly, Tesla's equipment and spectacular demonstrations with electrical discharges that look like strokes of lightning using his famous Tesla coil [23] attracted attention of artists interested in "electric performances art". These demonstrations are frequently shown in science museums and incorporated in performance pieces [34].

XIII. Concluding Remarks

Hughes points out in his book [9] that "Of the great construction projects of the last century, none has been more impressive in its technical, economic, and scientific aspects, none has been more influential in its social effects, and none has engaged more thoroughly our constructive instincts and capabilities than the electric power system." It can be added that of all of those involved, none has been more individually significant than Nikola Tesla. The scope and depth of his other contributions make him a far greater figure in the history of engineering. The omnipresence of his ideas, modestly sampled in this paper, shows that his greatness has withstood the test of time.

Acknowledgment

The author would like to thank Dr. Zorana Ercegovac for help in locating and accessing literature sources, Dr. Vuk Ercegovac for comments, and Mr. Dušan Hristović for useful suggestions regarding Tesla's work.

References

[1] M. Cheney, *Tesla Man Out of Time*, Englewood Cliffs. Prentice-Hall, Inc., 1981, p. xvi.

[2] D. C. Duffy, O. J. A. Schueller, S.T. Brittain and G. M. Whitesides. "Rapid prototyping of microfluidic switches in poly(dimethyl siloxane) and their actuation by electro-osmotic flow." J. Micromech. Microeng. 9, pp. 211-217, 1999.

[3] J.F. Elliott, "Thermomagnetic Generator," J. of Applied Physics, Vol. 39, No. 11, pp. 1774-1777, November 1959.

[4] A. Elsenaar and R. Scha, "Electric Body Manipulation as Performance Art: A Historical Perspective." Leonardo Music Journal, Vol. 12, pp. 17-28, 2002.

[5] F. K. Forster, R. L. Bardell, A. P. Blanchard, M. A. Afromowitz, and N. R. Sharma, "Micropumps With Fixed Valves." U.S. Pat. 5,876,187, Mar. 2, 1999.

[6] F. K. Forster, R. L. Bardell, and N. R. Sharma, "Method for Making Micropumps." U S. Pat. 6,227,809, May 8, 2001.

[7] V. A. Godyak, "Bright idea: Radio-frequency light sources." IEEE Industry Application Magazine, pp. 42-49, May-June, 2002.

[8] Haynes J.D. and Rees G. "Decoding mental states from brain activity in humans." Nature Reviews Neuroscience 7 (7): 523-534 July 2006.

[9] Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore and London, The Johns Hopkins University Press, 1988.

[10] E. Katz, Department of Chemistry, The Hebrew University of Jerusalem Givat Ram, http://chem.ch.huji.ac.il/ eugeniik/history/arsonval.html

[11] M.D. Kuzmin and A.M. Tishin, "Magnetocaloric effect. Part 1: An introduction to various aspects of theory and practice." Cryogenics, Vol. 32, No. 6, pp. 545-558, 1992.

[12] O. E. Langland and R. P. Langlais, "Early pioneers of oral and maxillofacial radiology." Oral and Maxillofacial Radiology, Vol. 80, No. 5, pp. 496-511, November 1995.

[13] A. Leidl, R. Hartinger, M. Roth, and E. Endres, "A new SO_2 sensor system with SAW and IDC elements." Sens. Actuators B, Chem., vol. B34, no. 2, pp. 339-342, Sept. 1996.

[14] A. V. Mamishev, K. Sundara-Rajan, F. Yang, Y. Du, and M. Zahn. "Interdigital Sensors and Transducers." Proceedings of the IEEE, Vol. 92, No. 5, pp.808-845, May 2004.

[15] K.B. Manning and G.E. Miller. "Shaft/Shaft-Seal Interface Characteristics of a Multiple-Disk Centrifugal Blood Pump." Artificial Organs, 23(6):552-558, 1999.

[16] I. R. McNab, "Homopolar Generators for Electric Guns", IEEE Transactions On Magnetics, Vol. 33, No.1 , pp. 46-467, January 1997.

[17] C. J. Morris, Member, and F. K. Forster, "Low-Order Modeling of Resonance for Fixed-Valve Micropumps Based on First Principles." Journal of Micromechanical Systrems, Vol. 12, No. 3, pp.325-334, June 2003.

[18] E. Paulos and J. Canny, "Ubiquitous tele-embodiment: applications and implications." Int. J. Human-Computer Studies (1997) 46, 861-877.

[19] D. J. Rhees, "Electricity"The Greatest of All Doctors": An Introduction to High Frequency Oscillators for Electro-Therapeutic and Other Purposes." Proceedings of the IEEE, Vol. 87, No. 7, pp. 1277-1281, July 1999.

[20] N. Tesla, "Experiments with alternating current at high frequency and their application to methods of artificial illumination." Elec. Eng., vol. 7, p. 549, 1891. Reprinted in *The Inventions, Researches, and Writings of Nikola Tesla*, pp. 145 - 197, Ed. T.C. Martin, New York, Barnes & Noble Books, 1992.

[21] N. Tesla, "Notes on a unipolar dynamo." The Elec. Eng.,:N.Y., Sept. 2, I89 I . Reprinted in *The Inventions, Researches, and Writings of Nikola Tesla*, pp. 465 - 474, Ed. T.C. Martin, New York, Barnes & Noble Books, 1992.

[22] N. Tesla, "Electric condenser." U.S. Patent 464 667, 1891.

[23] N. Tesla, "My Inventions: The Autobiography of Nikola Tesla." B. Johnson (Ed.), Hart Brothers, Williston, VT (1919/1982).

[24] N. Tesla, "Pyromagneto-Electric Generator." US Patent 428 057, 1890.

[25] N. Tesla, "Turbine." U.S. Patent No. 1,061,142, May 6, 1913.

[26] N. Tesla, "Valvular Conduit." U.S. Patent 1 329 559, 1920.

[27] N. Tesla, "Tremendous New Power to be Unleashed." Kansas City Journal-Post (10 Sep 1933).

[28] N. Tesla, "High frequency oscillators for electro-therapeutic and other purposes," Proc. IEEE, vol. 87, no. 7, pp. 1282-1292, July 1999.

[29] N. Tesla, "On the hurtful actions of Lenard and Roentgen tubes." Elect. Rev. 30:252, 1897.

[30] B.P. Turner, M.G. Ury, Y. Leng, and W.G. Love, "Sulfur lamps-progress in their development." Proc. IES Annu. Conf., p. 87, 1985.

[31] P. Woias, "Micropumpspast, progress and future prospects." Sensors and Actuators B 105 (2005) 28-38.

[32] T. G. West, "Advanced Interaction: A Return to Mental Models and Learning by Doing." Comput. & Graphics, Vol. 18, No. 5, pp. 685-689, 1994.

[33] T. G. West, *In the Mind's Eye: Visual Thinkers, Gifted People with Learning Difficulties. Computer Images, and the Ironies of Creativity*. Prometheus Books, Buffalo, NY (1997).

[34] S. Wilson, *Information Arts: Intersections of Art, Science and Technology* , Cambridge, MA: MIT Press, 2002, pp. 409-411.