

Innovative Engineering Education Using Programmable Lego Robotic VD Graaf Generators

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Abstract

The Technology Assisted Science, Engineering and Mathematics (TASEM) learning, with major focus on innovations in the use of technology to explain new and complicated concepts rather than on education research, goes far beyond the conventional demos of van de Graaf (VDG) generators to introduce programmable Lego-based VDG (PLVDG) for the first time. The PLVDG modules explain underlying concepts of micro- and nano-systems in a fun and fascinating way as evident from the level of interest seen in over 200 learners at K-12, undergraduate and graduate levels during 2006-07. The interest in PLVDG seems to be strongly related to the fact that the learners can design, build, program and explore PLVDG using different pulley & belt materials and a palm-size robot. The generated voltages are in the range of 5 – 35 kV depending upon humidity and pulley speed. Sensors of positive and negative charges have also been developed using NMOS and PMOS switches embedded in Lego-like bricks. A number of experiments are reported in this paper focusing on learning of a number of areas including materials, engineering (EE&ME), computers, and microsystems. The PLVDG-based learning modules will be marketed by Nanobrick.com.

Introduction

The prevalence of new technologies in old and new consumer products emphasizes the need to explain to both the formal and informal learner about (a) technologies that are in the market today as well as those that will be there in the near future and (b) how these technologies are used to build micro- and nano-systems. As the explanation of the underlying concepts in new technologies can be very challenging, traditionally efforts to increase impact of informal as well as formal learning techniques have focused on a restructuring of school science around real-world problems [1], inquiry based studies [2][3][4][5] including Design-Based Science (DBS) [6][7][8][9][10][11][12][13][14][15] and Learning By Design (LBD) [16][17][18], augmented reality (AR) [19][20][21][22][23][24][25], and Technology Assisted Science, Engineering and Mathematics (TASEM) [26][27][28]. A unique feature of the TASEM program is that it, encompassing a number of inquiry-based hands-on ideas, focuses on current and future technologies and it is capable of dealing with a variety of learning concepts and environments studied by other researchers [29][30][31][32][33][34][35][36][37][38][39]. Because TASEM is based on technology, it can address (a) technological learning issues in a unique way and (b) attempt very difficult and dry topics. One example is the explanation of a microcontroller (μ C), its building blocks, and their fabrication/operation.

A microcontroller is a computer chip that is the brain of today's consumer products including those based on micro- and nano-systems. It is a computer-on-a-chip suitable for applications that require high integration, low power consumption, and low cost. An electrostatic switch, called an MOS (Metal Oxide Semiconductor) transistor, is the basic building block of a microcontroller. Using the basic MOS concept different types of computer switches are made, which are needed for computing and memory devices. Some examples are n-channel MOS (NMOS), PMOS (p-channel), and CMOS (a complementary combination of NMOS and PMOS). As an NMOS switch is operated by a positive static charge and a PMOS switch is operated by negative static charge, they can be used as inexpensive sensors for static charges. That also means that NMOS and PMOS switches can be used to switch a number of other devices such as beepers, motors, fans, toys, etc. Such simple and inexpensive devices can be fun to play with on one hand and can help learn science, engineering and mathematics (SEM) on the other.

The NMOS and PMOS switches can also help study static charges and understand their adverse affects on microcontrollers and microprocessors. For example, static charges generated on the human body present in a car can damage car's computer circuits and make it non-functional even if its engine and other mechanical parts are still functional. The mightiest display of static charges is found in lightning. For the first time, the TASEM program uses Programmable Lego-based Van de Graaff (PLVDG) generators to learn about static charges, NMOS and PMOS switches, static charge sensors, system design and fabrication, and micro-structures. The PLVDG modules explain the underlying concepts of micro- and nano-systems in a fun and fascinating way as evident from the level of interest seen in over 200 learners at K-12, undergraduate and graduate levels during 2006-07.

Van de Graaff Generators

The Van de Graaff generator which was developed, starting in 1929, by physicist Robert J. Van de Graaff at Princeton University, is the twentieth century's contribution to the lineage of static electricity. In 1933, he demonstrated his machine that produced 1 million volts and was only a few feet tall [43]. VDG generators have been used in the fields of nuclear research [44][45][46] and medical radiations [47]. Van De Graaff Generators have also been used for fun and science experiments. A Frankenstein Demonstration [48], induction and repulsion with soap bubbles [49], and candle on a VDG [50] are some examples of early experiments. Other interesting experiments using Van de Graaff generators, described on different websites, are mainly based on the induction and repulsion between light objects and VDG globe [51].

A VDG is an electrostatic machine which uses a moving belt to generate very high voltages (in the range of 5 – 35 thousand volts for toy VDG and up to 14 million volts for commercial VDG) on a hollow metal globe. Fig. 1 shows how the positive and negative charges are separated and transferred to globe and the ground electrode, respectively. For example, if the lower pulley is made of ebonite or Teflon the process of rubbing will make it negative inducing a positive charge on the outside surface of the belt. As the belt moves up it brings the positive charge inside the globe, where the brush 2 picks it up through sparking. Because the like-charges repel each other they move to the outside surface of the globe (which is made from a conducting material such as a metal) where there is a larger surface area available making it possible for them to stay away from each other. If the upper pulley is made from leather or nylon, a similar process will transfer negative charge to the negative electrode, usually connected to ground.

The charges on the globe lead to an electrostatic voltage which depends on humidity level, pulley materials, belt speed and globe size. There is a theoretical maximum potential to which a VDG dome can be raised [52]. The electric field E of a sphere with a charge

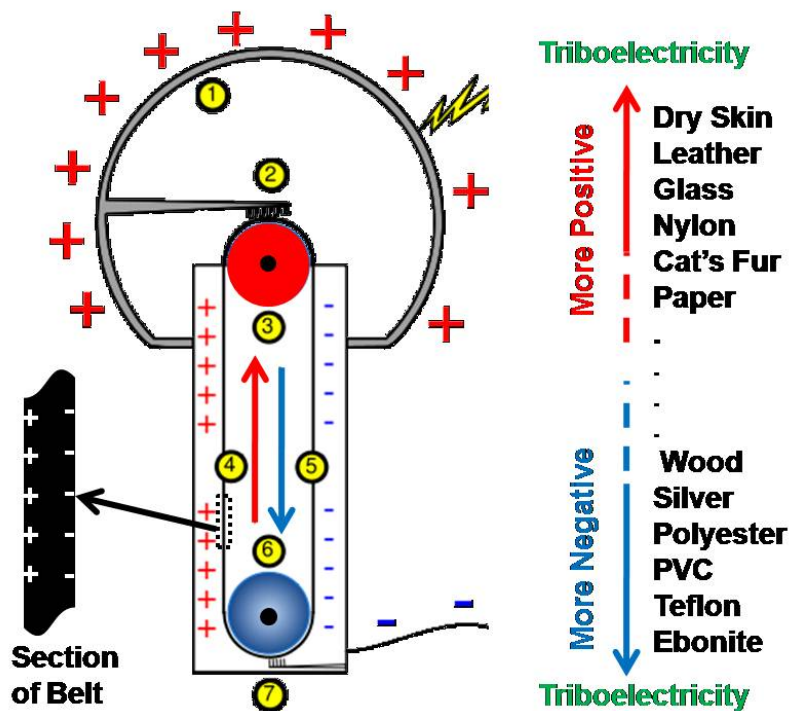


Fig. 1 Schematic of a VDG generator; (1) globe, (2) charge pickup brush, (4 & 5) sections of belt, (3 & 6) pulleys, (7) frame holding the pulleys and globe.

Q is given by

$$E = \frac{Q}{4\pi\epsilon_0 r^2} \quad (1)$$

for any radius r greater than the radius of the sphere. The capacitance of an isolated sphere of radius a is given by:

$$C = 4\pi\epsilon_0 a \quad (2)$$

Therefore, at the radius a of the sphere (assuming $a = r$), using (1) and $Q=CV$, E is given by:

$$E = \frac{CV}{4\pi\epsilon_0 r^2} = \frac{V}{a} \quad (3)$$

Or:

$$V = Ea \quad (4)$$

The maximum potential V_B for the dome, the breakdown potential, is such that the air can no longer sustain the electric field at the surface of the dome, and breakdown of the air occurs. For dry air at standard temperature and pressure, the maximum sustainable electric field is about 30,000 V/cm, so

$$V_B = 30,000 a \text{ V} \quad (5)$$

where a is the radius of the dome in centimeters and V stands for volts.

Lego-Based Van de Graaff Generators

For the first time, this paper reports the design, fabrication and testing of toy VDG generators using plastic bricks [53], similar to Lego and Megablock pieces. With the exception of belt, the pulleys and globe, which are custom made to fit the brick construction, all parts are made using commercially available bricks, plates, beams, axles, Lego motors, and Robotics Invention System. Fig. 2 shows the first version of a robotic VDG.

Examples of Experiments

A number of interesting experiments have been developed, which explain static charges, NMOS and PMOS switches, static charge sensors, system design, and micro-structures. As the modules range from very basic to very advanced, their description and related learning are categorized (according to their degree of difficulty) for different audience levels; **L** (Lay audiences), **K** (K-12 audiences), **C** (College audiences), and **P** (Professional, undergraduate & graduate audiences).

Activity 1: L, K, C, P

- Rub a nylon-polyester cloth on a polycarbonate plastic sheet, and bring the plastic sheet near a simple static charge sensor (called an electroscope, Figure 3). What happens?

Explanation: When the electroscope is brought near a source of static electricity, some of the electrons in the leaves (Figure 3) are pulled up to the hook away from the leaves if the source is positive, or pushed towards the leaves if the source is negative. In either case, the leaves have the same type of charge and so they repel each other. The



Fig. 2 Programmable robotic VDG generator; miniaturization of VDG and a close-up of upper pulley and brush.

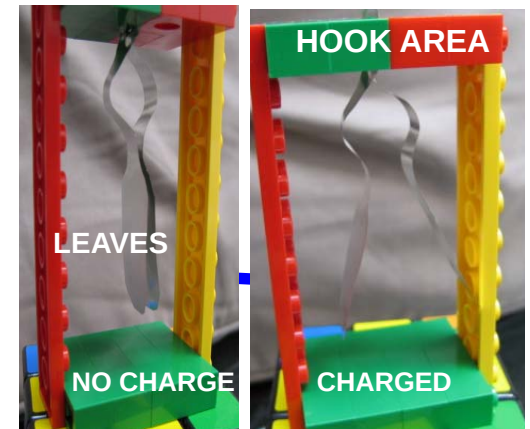


Fig. 3 Lego electroscope as an inexpensive sensor for static charges; the leaves are made from Al foil that is typically used in a kitchen.

distance they open up is proportional to the charge of the source (if the sources are always held at the same distance from the hook).

- Now build an RCX robot (Robotics Invention System) and learn how to program it.
- As shown in Fig. 4, attach an NMOS transistor to one of the sensor ports and program the RCX for light sensor on this port.
- Now program the robot to find a positive static charge, go around the source of static charge or run away from the static charge source such as polycarbonate sheet. This should be possible because the NMOS switch acts as a sensor for positive static charge.

Activity 2: K, C, P

The electroscope used in the above activity does not detect the type of charge (positive or negative). To detect the type of charge, you can use electronic sensors called NMOS or PMOS switches. The NMOS is switched on by a positive charge and the PMOS is switched on by a negative charge. The NMOS we use is **BS 170** and the PMOS is **BS 250** (available from Jameco Electronics for \$ 0.10).

- As the robot was equipped with an NMOS sensor, the charge on the polycarbonate sheet must be positive.
- Now attach a PMOS sensor to another port of the robot and change the program to detect both positive and negative charges.
- To understand the operation of NMOS and PMOS sensor switches and related electronic circuits, see sensor development procedure shown in Figure 5. The breadboard is used to build the simple circuit.
- Referring to the breadboard, you will find that the LED in the NMOS area of the Sensor lights up, meaning that the charge on the polycarbonate sheet is **positive**. Now try rubbing different materials on cloth (also use different types of cloths, plastic sheets, etc.) to find the type and strength of the charges that you generate for different materials.
- Prepare a summary of your observations.

Activity 3: K, C, P

The static charges can be used to understand the basic operation principle of microsystems (or MEMS). In microsystems, mechanical parts such a beam can be moved by charges. Although, the MEMS components are typically in micrometers, in our experiments, we use a larger structure, which can be called Electro Mechanical Systems (EMS):

- Charge the polycarbonate sheet.
- Move the sheet over the structures shown in Figure 6 and see what happens.

Explanation: The face and arms of the little humanoid move when you bring the charged sheet close to it. Similarly, the bridges and beams move and vibrate if the charged polycarbonate sheet is brought close to the structures. When the sheet is brought near the free end of the beam, the induction of charges (separation of positive and negative charges within the beam) in the beam depends on whether the beam is a conductor (Figure 7) or insulator (Figure 8). In either case, there is a force of attraction between the positive and negative charges and the free end moves towards the sheet.

A similar principle is used in an electrostatic micrometer-size acceleration sensor (accelerometer) that is used to trigger the airbag in a car. Such a device is also used in the wireless controller of Nintendo's exciting new Wii video gaming system.

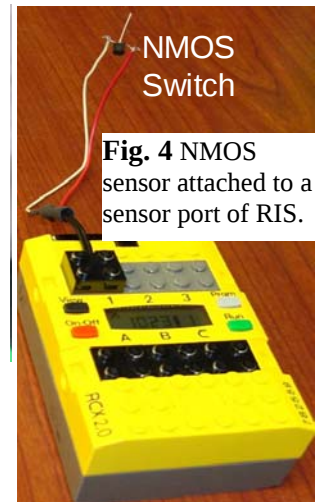


Fig. 4 NMOS sensor attached to a sensor port of RIS.

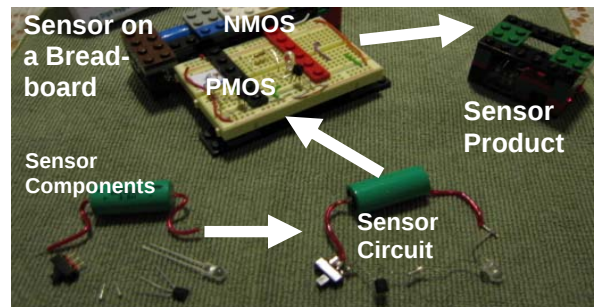


Fig. 5: Sensor development; from circuit to product.

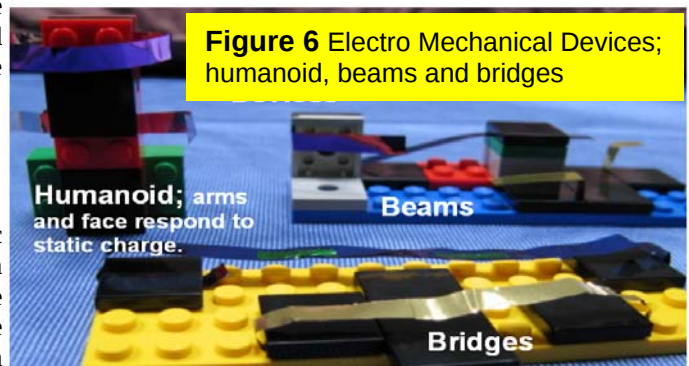


Figure 6 Electro Mechanical Devices; humanoid, beams and bridges

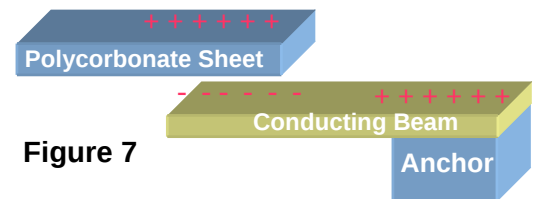


Figure 7

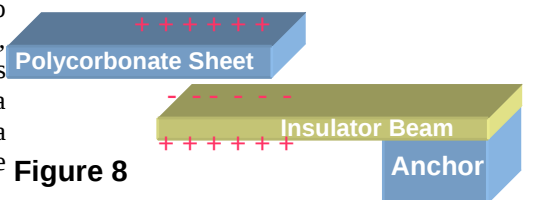


Figure 8

Activity 4: K, C, P

Hold one lead of a neon bulb and bring the other lead close to a charged polycarbonate sheet (Figure 9). The bulb blinks once because the charge on the sheet affects the neon gas inside the bulb. The gas atoms split into positive and negative particles (Neon plasma), which produce light. Move the bulb over another part of the sheet and it blinks again. Why does it blink again?

Does the charge on the polycarbonate sheet move if it is brought near another charged object? If you touch one end of the sheet, does all the charge disappear from the sheet? Get the answer to these questions by doing experiments. For example charge the sheet and then touch parts of the sheet with your hand. Is the sheet totally discharged when you touch one of it? Try rubbing your hand on all parts of the sheet.

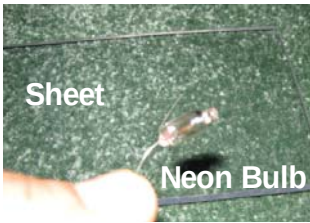


Fig. 9 Neon bulb near a charged sheet.

Activity 5: K, C, P

- Connect the motor of a van de Graaff generator (Fig. 2) to the port A of the RCX. Program the RCX to run the motor A at maximum speed. Now bring the electroscope closer and closer to the top globe of the Van de Graaff generator until its leaves go apart. Record the distance, between the electroscope and the globe, in the table below.
- Now program the RCX to run the motor A at a lower speed. Repeat the above procedure and record the distance in the table.
- Repeat the above procedure for another motor speed.

A **Plasma** typically consists of positive and negative particles in a gas. These particles, if they have a charge on them, are called ions. Thus, plasma is an ionized gas. The presence of free or mobile electric charges makes the plasma electrically conductive.

Activity 6: C, P

- Program the RCX to run the motor A at maximum speed. Measure the globe voltage using the electrostatic charge meter and record in the table below. Now bring the NMOS charge sensor closer and closer to the top globe of the Van de Graaff generator until one of its LEDs lights up. Measure the distance between the globe and the sensor. Record the distance in the table below.
- Now program the RCX to run the motor A at a lower speed. Repeat the above procedure and record the distance in the table.
- Repeat the above procedure for another motor speed.
- Measure the electrostatic voltage of the polycarbonate sheet after you charge it. Compare this voltage with the voltages of the globe of the van de Graaff generator for different speeds of the belt.
- Try different globe sizes and see if equation (5) can be tested.

Motor Speed	Voltage of Globe (Volts)			Electroscope Distance (cm)			NMOS Sensor Distance (cm)		
	1 st Try	2 nd Try	3 rd try	1 st Try	2 nd Try	3 rd Try	1 st Try	2 nd Try	3 rd Try

Activity 7: C, P

- Demonstration of a tiny plasma reactor. This Lego-based construction shows a neon plasma inside a neon bulb (Figure 10). Bringing it near the van de Graaff generator globe lights up the neon gas.
- You will find that the plasma light, caused by the charge on the globe of van de Graaff generator, blinks. Why does the plasma light blink?

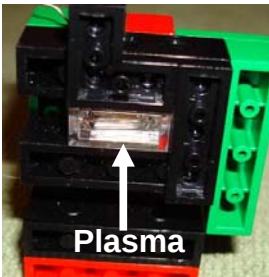


Fig. 10 Neon plasma reactor.

Expected Impact

Table 1 shows the possible impact on different audiences in different settings and

environments. The efficacy of the program discussed in this paper is based on teaching at the undergraduate/graduate (formal) and K-12 (informal) levels. It may be pointed out that no formal education research was conducted to generate the Table 1. Thus, the data provided here is qualitative and is based on the assessment of instructors, parents and other professional observers (one of the observers had a doctorate in education) during 2006-07.

Table 1 Learning level (Basic, Intermediate, Advance), underlying STEMS areas (S, T, E, M), expected impact (Low, Normal, High), learner interest (Low, Normal, High), possible audience types (Families, Children, Adults, College Students, Teachers, Professionals, Underserved, Retired, Boy Scouts, Hobbyists and Explorers), and possible locations (Museum, Science & Technology Center, Community Center, Mall and Shopping Center, Library, Websites, After-School Locations).

Gen. Area	Sub Areas	Learning Level: B, I, A	STEM Areas	Expected Impact: L, M, H	Learner Interest : L, M, H	Audience Types: F, C, A, S, T, P, U, R, B, E	Possible Location: M, T, C, S, L, W, A	Unique Aspect
Van de Graaff Generators	Static Charges	B, I, A	S, T, E	H	H	All	M, T, C, S, L, A	Explain switches/gates
	Coputer Switches & Sensors	I, A	S, T, E	M	M, H	All	M, T, C, S, L, A	Lego VDG Generators
	VDG Design	A	S, T, E	L	M	A, S, T, P, U, E	T, C, W	Use of Legos

Conclusions and Future Plans

Focusing on technology innovations, rather than education research, this paper reveals for the first time Lego-based Van de Graaff generators field-tested on approximately 200 K-12, undergraduate and graduate students. As most of the educators in engineering in the US have doctoral degrees in research areas related to engineering fields, their knowledge and focus on education research is limited. On the other hand most of those who have doctoral degrees in education research are less focused on the use of latest micro and nanotechnologies in their everyday research work. Consequently, it has become difficult to develop research partnerships with education researchers particularly in the areas of new technologies. Nevertheless the future plans of the research reported in this paper include the development of active collaborations with education researchers for the formal conduction of education research which will be reported in future publication.

Acknowledgement

This work was partly supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.

REFERENCES

- [1] Lipman, M. (1991). Thinking in education. New York: Cambridge University Press.
- [2] CTGV. (1992). The jasper series as an example of anchored instruction: Theory, program description, and assessment data. Educational Psychologist, 27(3), 291-315.
- [3] Krajcik, J. S., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. The Journal of the Learning Sciences, 7(3&4), 313-350.
- [4] Penner, D. E., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design-based modeling approach. The Journal of the Learning Sciences, 7(3&4), 429-449.
- [5] Songer, N.B. (1996). Exploring learning opportunities in coordinated network-enhanced classrooms: A case of kids as global scientists. Journal of the Learning Sciences, 5, 297-328.
- [6] D. Fortus, R.C. Dersheimer, J. Krajcik, R.W. Marx and R. Mamlok-Naaman, design based science and student learning, J. Research Sci. Teaching, 41, 1081-1110 (2004).
- [7] Roberts, P. (1995). The place of design in technology education. In D. Layton (Ed.), Innovations in science and technology education (pp. 27-38). UNESCO.
- [8] Baynes, K. (1994). Designerly play. Loughborough, UK: Loughborough University of Technology.
- [9] Simon, H.A. (1999). The sciences of the artificial. Cambridge, MA: MIT Press.
- [10] Bucciarelli, L.L. (1994). Designing engineers. Cambridge, MA: MIT Press.
- [11] Davis, M., Hawley, P., McMullan, B., & Spilka, G. (1997). Design as a catalyst for learning. Alexandria, VA: Association for Supervision and Curriculum Development.
- [12] ITEA. (2002). Standards for technological literacy. Reston, VA: International Technology Education Association.

- [13] NRC. (1996). National science education standards. Washington, DC: National Academy Press.
- [14] NRC. (2002). Scientific research in education. Washington, DC: National Academy Press. Penner, D.E., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design-based modeling approach. *Journal of the Learning Sciences*, 7, 429–449.
- [15] Chiapetta, E.L., Koballa, Jr., T.R., & Collette, A.T. (2002). Science instruction in the middle and secondary schools (5th ed.) Upper Saddle River, NJ: Prentice-Hall.
- [16] Kolodner, J.L. (1993). Case-based reasoning. San Mateo, CA: Morgan Kaufmann.
- [17] Kolodner, J.L., Crismond, D., Gray, J., Holbrook, J.K., & Puntambekar, S. (1998). Learning by design from theory to practice. Presented at the International Conference of the Learning Sciences, Georgia Tech University, Atlanta GA.
- [18] Barrows, H.S. (1985). How to design a problem-based curriculum for the preclinical years. New York: Springer.
- [19] Azuma R. A Survey of Augmented Reality. *PRESENCE: Teleoperators and Virtual Environments*, Vol. 6, No. 4, pp. 355-385, 1997.
- [20] Osberg K. Spatial Cognition in the Virtual Environ., Technical R-97-18. Seattle: Human Interface Technol. Lab, 1997.
- [21] Rizzo AA, Buckwalter JG, Neumann U, Kesselman C, Thiebaut M, Larson P, and van Rooyen A. The Virtual Reality Mental Rotation Spatial Skills Project. In *CyberPsychology and Behavior*, 1(2), pp. 113-120, 1998.
- [22] Pantelidis, V. S. Reasons to Use Virtual Reality in Education, *VR in the Schools* 1(1), 1995. URL: <http://www.soe.ecu.edu/vr/reas.html> (Revised 2000).
- [23] Roussos, M., Johnson, A., Moher, T., Leigh, J., Vasilakis, C., and Barnes, C. Learning and Building Together in an Immersive Virtual World. *PRESENCE* 8(3), pp. 247-263, MIT Press, June 1999.
- [24] Winn, W. A Conceptual Basis for Educational Applications of Virtual Reality, Technical Report TR 93-9: <http://www.hitl.washington.edu/publications/r-93-9/>, 1993.
- [25] Zagoranski, S. and Divjak, S., Use of augmented reality in education, *EUROCON* 2003, 2, 339-342.
- [26] D.M. Aslam, "Micro- and Nano- Technologies in K through Ph.D. Education and Research", Keynote, Second World Congress Biomimetics, Artificial Muscles and Nano-Bio (Nano-Bio 2004) Albuquerque, New Mexico, December 6-8, 2004.
- [27] D.M. Aslam, "Small Tech Education", Keynote, High Desert MNT Regional Workshop, TVI Workforce Training Center - Albuquerque, NM, October 12-13, 2004.
- [28] D.M. Aslam, "Technology Assisted Science, Engineering and Mathematics (TASEM) Education at all Levels Using K-Ph.D. Concept", *Proc. ASEE Annual Conference*, Chicago, 92, 2006.
- [29] Heimlich, J., Editorial, *Environmental Education Research* 11(3): 261-264 (2005).
- [30] Dierking, L.D., Ellenbogen, K.M. & Falk, J., "In Principle, in Practice: Perspectives on a decade of museum learning research (1994-2004)", *Science Education* 88: S1-3 (2004).
- [31] Dierking, L.D.; Cohen Jones, M.; Wadman, M.; Falk, J.H.; Storksdieck, M. & Ellenbogen, K., "Broadening Our Notions of the Impact of Free-Choice Learning Experiences", *Informal Learning Review* 55, 1, 4-7 (2002).
- [32] Allen, S., "Designs for learning: Studying science museum exhibits that do more than entertain", *Science Education* 88, S17-33 (2004).
- [33] Myers, D. (2003). *The nature of computer games: Play as semiosis*. New York: Peter Lang Publishing.
- [34] Squire, K. (2002). Cultural framing of computer/video games. *The International Journal of Computer Game Research* 2: 1.
- [35] Wright, J.C., Anderson, D.R., Huston, A.C., Collins, P.A., Schmitt, K.L. & Linebarger, D.L. (2001). The effects of early childhood TV-viewing on learning. In Falk, J.H. (Ed.). *Free-choice science education: How we learn science outside of school*, pp. 79-92, New York: Teachers College Press.
- [36] Ellenbogen, K.M., Luke, J.J. & Dierking, L.D. (2004). Family learning research in museums: An emerging disciplinary matrix? *Science Education* 88: 48-58.
- [37] Rounds, J. (2004). Strategies for the curiosity-driven museum visitor. *Curator* 47: 389-412.
- [38] Azevedo, F.S. (2004). *Serious Play: A comparative study of learning and engagement in hobby practices*. Unpublished doctoral dissertation. University of California, Berkeley.
- [39] Storksdieck, M., Ellenbogen, K. & Heimlich, J.E. (2005). Changing Minds? Factors that influence free-choice learning about environmental conservation. *Environmental Education Research* 11(3): 93-109.
- [40] G. Wile and D.M. Aslam, "Design, Fabrication and Testing of a Miniature Wall Climbing Robot Using Smart Robotic Feet", *Proc. International Conference on Cybernetics and Information Technologies, Systems and Applications*, Edited by M. Saavoie et al., Vol. III, 87-92 (2007).

- [41] L. C. McAfee, K. Najafi, Y. Gianchandani, K. D. Wise, and M. M. Maharbiz, D.M. Aslam, P. Bergstrom, C. Friedrich,, "MEMS and Microsystems Courses with National and International dissemination", Proc. ASEE Annual Conference, Chicago, 84, 2006.
- [42] L. C. McAfee, K. Najafi, Y. Gianchandani, K. D. Wise, and M. M. Maharbiz, D.M. Aslam, P. Bergstrom, C. Friedrich, "A MEMS/MICROSYSTEM CURRICULUM WITH INTERNATIONAL DISSEMINATION ", Proc. Hilton Head, 2006.
- [43] Robert J. Van De Graaff, "The Electrostatic Production of High Voltage for Nuclear Investigations" Phys. Rev., vol. 43, 149, 1933
- [44] B. L. Doyle, P. S. Peercy "Technique for profiling 1H with 2.5-MeV Van de Graaff accelerators" Appl. Phys. Lett. 34, 811 (1979);
- [45] MJ Burchell, etc., "Hypervelocity impact studies using the 2 MV Van de Graaff accelerator and two-stage light gas gun of the University of Kent at Canterbury" Meas. Sci. Technol 10 (1999) 41-50
- [46] Belli, M. etc., "Proton irradiation facility for radiobiological studies at a 7 MV Van de Graaff accelerator" Nuclear Instruments and Methods in Physics Research Section A, Volume 256, Issue 3, p. 576-580.
- [47] Rydin R.A. Engler R.A., "15O and 13N production by Van de Graaff accelerator" Physics in Medicine and Biology, Volume 19, Number 6, 1974, pp. 884-885(2)
- [48] James G. Ellingson, "A Frankenstein demonstration with the Van de Graaff generator" The Physics Teacher, Volume 26, Issue 7, pp. 446-446 (1988)
- [49] Robert Prigo, "Demonstration induction and repulsion with soap bubbles and the Van de Graaff generator" Am. J. Phys. Vol. 44, No. 6, June 1976
- [50] Motoji Ikeya, Hiroshi Matsumoto, "Reproduced earthquake precursor legends using Van de Graaff generator: candle flame and dropped nails." Naturwissenschaften 84, 539–541 (1997)
- [51] <http://demo.physics.uiuc.edu>, <http://128.174.130.156/LectDemo>, <http://demo.pa.msu.edu>, <http://demoroom.physics.ncsu.edu>, <http://www.pasco.com>.
- [52] Richard E. Berg, "Van de Graaff Generator: Theory, Maintenance, and Belt Fabrication" Physics Teacher, v28 n5 p281-85 May 1990
- [53] D. M. Aslam, pending patent, Michigan State University, 2007.