Design of a CAD Integrated Physical Model Rotator

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Abstract

Increasing the number of engineers is crucial to keep pace with the current demands for a high tech workforce. There are two critical concerns related to the shortage of engineers, retention of students in engineering disciplines and attraction of students into engineering fields. While not the only factor that influences retention and recruitment issues (others include peer support and mentoring), poor spatial ability skills may play a significant role. For example, the ability to correctly visualize three dimensional objects when they are represented in two dimensions, such as in Computer-Aided Design (CAD) software or in a detailed part drawing, is essential for engineers. Not surprisingly, due to self selection, engineering students typically score higher on spatial ability tests than their non-engineering counterparts. Research has shown that the spatial ability of engineering students will improve during a semester long CAD based design course and also that students prefer working with actual physical objects when developing these skills during a drafting course. However, whether the integration of an actual physical model with the CAD software can generate even greater improvement in spatial ability in both engineering and non-engineering students has not been investigated. In this paper, a CAD integrated Physical Model Rotator is proposed and details are provided with respect to its design and implementation. Future experiments are also discussed which will investigate the effectiveness of this educational tool to improve the spatial ability skills of a diverse population.

I. Introduction

The shortage of engineering students and the fear of the United States' losing its global technological advantage are well documented [1]. A report by the National Science Board estimated that the growth in engineering employment between 1994 to 2005 will be 35% while the enrollment in engineering fields has fallen consistently since 1979, approximately 1.6% annually [2]. There are two critical concerns related to the shortage of engineers, retention of students in engineering disciplines and attraction of students to engineering fields. While not the only factor that influences retention and recruitment issues, poor spatial ability skills may play a significant role due to the lack of confidence a student feels during introductory engineering courses and while performing crucial visualization tasks. As was stated by Bishop [3] and noted by several others [4-10], "good spatial conceptualization is not an asset but a necessity" for engineering as well as other math and science disciplines. Henderson [9], a sociologist, came to this conclusion after interviewing design engineers in over 30 companies, and Ferguson [10] stressed the importance of the "mind's eye", i.e. the ability to have a mental image and be able to mentally manipulate the artifact, during the design process. An example of this vital spatial skill for engineers is the ability to correctly visualize three dimensional objects when they are represented in two dimensions, such as in CAD software or in a detailed part drawing. Standardized tests have been developed to assess the spatial ability of individuals. See Fig. 1 for an example of a question from one such standard spatial ability test, the Mental Rotation Test [11], which was developed based on classic psychology research by Shepard and Metzler [12].

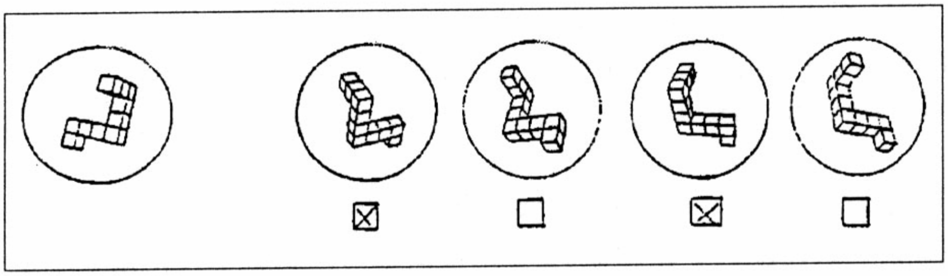

Figure 1. Example question from the Mental Rotation Test (MRT) [11].

The use of CAD software during introductory design engineering courses has been shown to improve the spatial ability skills of engineering students [4-7]. Sorby and Baartmans [4] developed a course at Michigan Technological University entitled “Introduction to Spatial Visualization” to improve the spatial ability of freshman students. The course included topics such as isometric and orthographic sketching, flat pattern development, and rotation of objects. Data analysis showed that the spatial ability skills of the students were significantly improved after enrollment in the course and that the retention rates in engineering disciplines increased from 62.5% to 69.2% for male students and from 53.1% to 63.6% for female students, for the control (n=72, 40 men and 32 women) and experimental (n=24, 13 men and 11 women) groups respectively. Furthermore, overall retention of female students at the technical university increased from 71.9% to 81.8%, for the control and experimental groups respectively. Hsi et al. [5] conducted a similar study in which students in an introductory design course, that were identified as “at risk” based on spatial problem solving tasks, were invited to attend a 3-hour session on strategies to improve their spatial ability skills. The results showed that pre-course gender differences were eliminated as a result of the spatial strategy instruction and that no students received a failing grade in the course after the training.

Miller [8] compared the spatial ability improvements of 75 students in an engineering graphics course using both CAD software and actual 3D objects. The students were first tested to classify their learning styles. They were then given one of three treatments, the traditional paper graphics curriculum solely, the traditional curriculum supplemented with real physical models, or the traditional curriculum supplemented with CAD software training. The results did not show a statistically significant difference between the three treatment types. However, students in a post-course questionnaire indicated that a combination of all three treatments would be the best instructional technique (51%) followed by real models only (33%) and CAD models only (10%). Therefore, incorporation of actual 3D objects into the design curriculum is favored by students in this study. However, a concern with manually manipulated physical models is that the students may not orient the object correctly during visualization tasks.

The above mentioned studies where the improvements in spatial ability led to improved retention rates were conducted with students already enrolled in engineering disciplines. The other concern with respect to the shortage of engineers is the attraction of students to engineering fields. Again, improving spatial ability, while not the only factor, may also help in this effort. This is due to increases in motivation with respect to these essential engineering skills and self-confidence the students would feel after spatial ability training.

In Education literature, motivation refers to "the process whereby goal-directed activity is instigated and sustained" [13]. Not surprisingly based on this definition, learning and performance are related in a reciprocal manner to motivation. Motivation is often thought of in terms of the interest or value a student would feel related to a given subject matter or task. However, motivational models in education and psychology stress the importance of the expectancy construct. Two key ideas within this construct are self-concept and self-efficacy both of which relate to self-confidence. Self-concept measures a student's general perception of confidence or ability regarding learning in a particular field, in this case engineering, whereas self-efficacy measures a student's perception of competence for handling specific tasks, here visualization tasks. Students who feel self-confident about learning or performing well at specific tasks will seek new challenges in a related area, apply more effort to learn new material, and persist longer at difficult tasks [14]. In contrast, most students will choose not to engage or continue in a task in which they expect to fail.

Research has shown that a student's expectancy beliefs regarding being able to succeed at a given task are closely related to actual achievement on standardized tests as well as course grades [15]. Bandura [16, 17] hypothesized that self-efficacy affects choice of activities (i.e. whether students would choice engineering), effort, and persistence (i.e. whether students would be retained in engineering). Furthermore, current research has shown that self-concept is also related in a reciprocal fashion to achievement and performance in school [13]. In order to measure students' self-confidence for a given task or subject matter, questionnaire surveys have been utilized, for example the Motivated Strategies for Learning Questionnaire [18].

Therefore, in order to foster retention and attraction of students into engineering disciplines, a means to effectively and efficiently improve their spatial ability must be developed. Furthermore, the exposure of high school and non-engineering students to novel and interactive devices, while simultaneously motivating them and improving their self-confidence (i.e. their self-concept and self-efficacy) and spatial ability skills, may attract students to engineering disciplines. In this paper, the concept and design of a CAD software integrated Physical Model Rotator (PMR) is presented. The implementation of the device to assess the spatial ability improvements and self-confidence of engineering and non-engineering students in future controlled experiments is also discussed.

II. Concept of the Physical Model Rotator

The PMR will be integrated into a CAD software package to allow an actual 3D object to rotate simultaneously with the model rotating on the computer screen and in the same field of vision for the user. See Fig. 2 for a schematic of the system. The rationale for this device is that users of the CAD package may not be able to visualize the 3D representation of the object on the 2D computer screen thus becoming discouraged or confused. The author has anecdotally witnessed this while teaching introductory design courses. By providing the user with an actual 3D object in the correct orientation, a perceptual connection will be made between the 3D object and the 2D representation on the computer screen, thereby improving the user's spatial ability skills. The goal is to assist the user in visualizing 3D objects in a 2D representation and develop the user's projective spatial skills, which are essential in creating and visualizing orthographic views of objects in detailed part drawings.

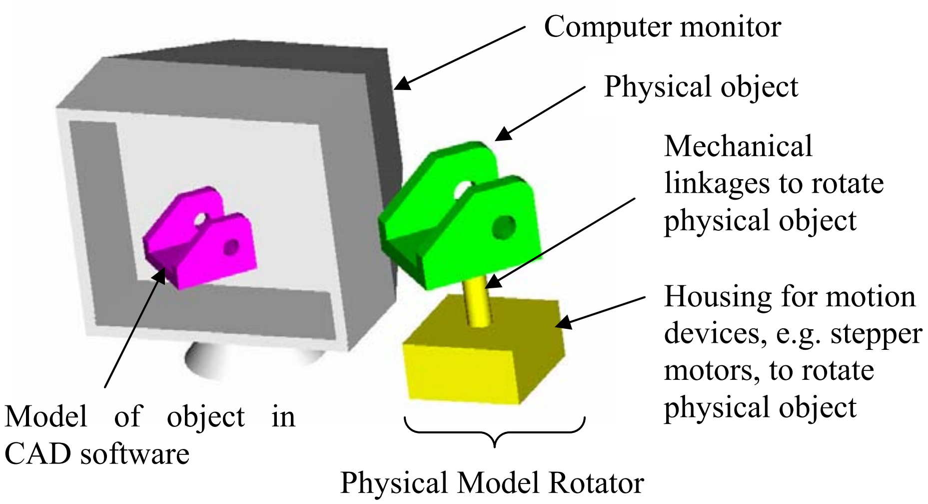

Figure 2. Schematic of CAD integrated Physical Model Rotator system.

In CAD software packages, the computer mouse and keyboard are used as the mechanisms for interaction with the software. Typically, the model of the part can be rotated, translated, and zoomed in and out on the computer screen by holding down certain keys on the keyboard and mouse buttons while simultaneously moving the mouse. Within the CAD software package, these actions amount to a transformation of the matrix of data which defines the model.

In order to obtain a similar part rotation of an actual 3D object simultaneous to the motion of the model on the computer screen, the transformation matrix data of the CAD model will be sampled. Then based on changes in the data file, an output signal will be sent to devices that drive the actual 3D object through a PCI output board in the computer. National Instruments Labview software and PCI output board will be used in the control system. See Fig. 3 for a functional flowchart of the PMR system. The preliminary design for the PMR uses stepper motors to rotate the 3D object. The motors will have an initial default position the same as that of the CAD model to allow the starting location of the model and the 3D object to be the same. More information regarding the selection of the motors for the PMR is given in the next section.

In order to have a seamless interaction between the CAD software and the PMR, Solidworks Corporation, which produces one of the leading CAD software packages on the market, and the author have entered into a Research Partnership. The CAD programming expertise, visualization knowledge, user interface skills, and software technical support Solidworks will provide to the project are crucial for its success. For instance, the author will work with Solidworks to understand, obtain, and utilize the transformation matrix data in order to determine the required output signal to the stepper motors to drive the physical 3D object and match the motion of the CAD model. Also, one of the challenges in this research will be the fact that the models in CAD software packages are able to rotate 360 degrees around on each axis. However, the mechanical linkages of the PMR may not allow this capability without visual interference from occurring. Solidworks already has access to software which will alleviate this concern by limiting the rotation of the model [19].

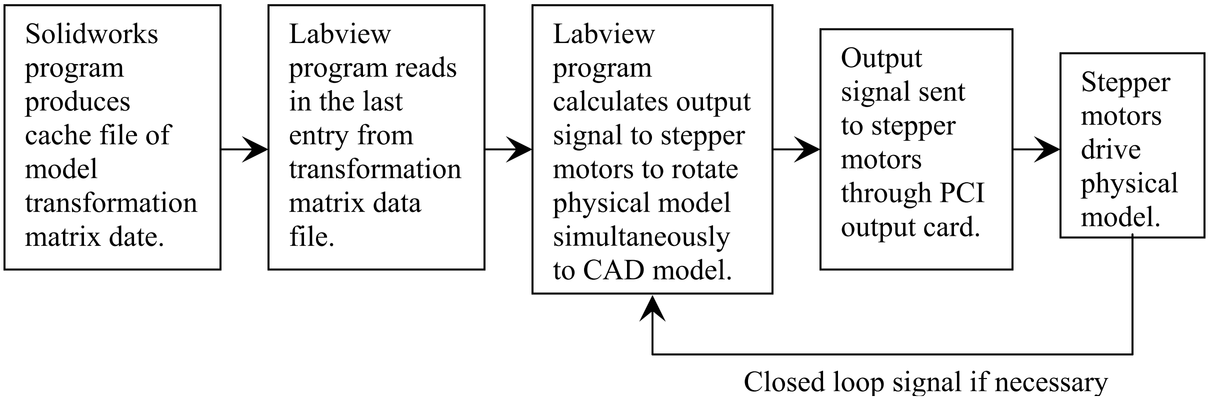

Figure 3. Functional flowchart of PMR device

III. Preliminary design of the Physical Model Rotator

A Mechanical Engineering senior design team, as part of their capstone design experience, undertook the prototyping of the PMR. The device was designed during the Fall semester of 2002 and will be fabricated during the Spring semester 2003. Some of the design criteria for the device were:

- Motion accuracy of physical object with respect to CAD model
- Speed of response
- Size of entire PMR device
- Safety for user
- Aesthetics
- Cost
- Manufacturability
- Design feasibility
- Durability

After brainstorming design alternatives and employing a decision matrix, the team selected a design which utilized 3 motors to completely rotate the physical object. See Fig. 4 for a schematic of the chosen design. The large motor drives one structural member which ends at the intermediate size motor. Another separate structural member, which is driven by the intermediate size motor, ends at the small motor. The physical object connects directly to the smallest motor.

To determine the size of the motors required, standard mechanics and machine design principles were applied. For example, the required torque from the motor was determined from:

$$M=I\alpha \qquad (1)$$

where M is the moment, I is the moment of inertia of the driven object/member, and α is the angular acceleration, which was set to be 2π rad/sec^2. The calculation of the moment provided the necessary torque of the motor and an appropriate safety factor was also included. In order to determine the moment of inertia, the object was considered to have a mass of 2-kg and be a cube with 15-cm sides. This mass is reasonable as the objects will be produced from a lightweight material such as plastic or foam. The size of the object was chosen to be adequate for visualization purposes but not too large to require motors with high torque capacity. The sizes of the motors selected are:

Largest motor: 36.5 N-cm
Intermediate motor: 22.2 N-cm
Smallest motor: 15.5 N-cm

These motors have 400 steps/revolution, thus achieving the accuracy requirement for the device. The speed of the motors in revolutions per minute was not a factor in the selection process since the mouse controls in the Windows operating systems will be used to limit the rotational speed of the model in the CAD software package.

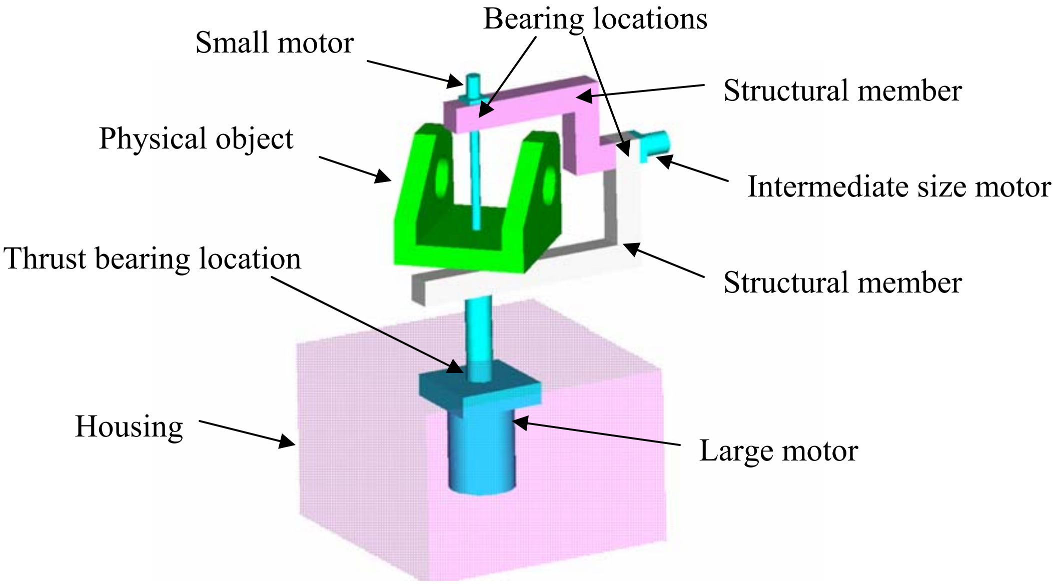

Figure 4. Schematic of the 3 motor design chosen for the Physical Model Rotator.

A thrust bearing will be used on the largest motor to assure an axial load due to the weight of the overall device is not exerted on the motor. Roller bearings will be used for the other two motors since axial loads will not be a concern. The structural members of the PMR will be created with extruded aluminum channeling and standard connectors to attach the various members. This will provide for a lightweight, flexible, and easy to fabricate structure.

In the Spring semester of 2003, the senior design team will be fabricating the prototype for the PMR. At this time other considerations will also be addressed. For instance, whether open loop control is satisfactory for the device or close loop control is necessary in order to accurately track the motion of the model in the CAD software package. Also, the actual physical objects will be fabricated at this time using building blocks, such as Legos, or machining to reduce fabrication costs and provide for ease in manufacturing. The shapes of the objects will be similar to those found in the MRT.

IV. Future experimental work

The goal of designing and building the PMR was to create a device which will improve the spatial ability skills of a diverse population for retention and attraction purposes in engineering. In order to assess the spatial ability improvements and self-confidence with respect to visualization tasks, a controlled experiment will be conducted with volunteer engineering undergraduates, non-engineering undergraduates, and high school students as the participants. For each demographic, the variables of major interest will be within-subject variables. Based on prior research employing similar experimental methods and questionnaire surveys, a minimum of 30 participants will be included in each within-subject group. See Table 1 for a summary of the number of participants in the study from each demographic. The large number of total participants in the research, 520, requires that several CAD integrated PMRs systems will need to be fabricated in order to provide for an efficient test procedure. This in essence is a Psychology experiment; therefore, the author will seek the assistance of Edward O'Brien, Professor in the Psychology Department at the University of New Hampshire, whose area of expertise is perception and cognition in psychology, for assistance with this aspect of the research.

	Control group	PMR group	Totals
High School Students			
Urban	30	30	60
Suburban	30	30	60
Rural	30	30	60
Non-eng. Undergraduates	30	30	60
Engineering Undergraduates		80	80
Totals	120	200	320

Table 1. Number of participants from each demographic. (PMR: Physical Model Rotator)

In order to assess the spatial ability improvements, participants will be required to complete the pencil and paper MRT both before the training with the PMR and approximately two weeks after the intervention. Because accuracy of responses on the MRT may not be sensitive to small or subtle changes in spatial ability, the time to produce a correct response will also be measured. Presumably, as spatial ability increases, the time to judge the rotation of an object should decrease. For each trial, two objects from the MRT will be displayed on a video monitor controlled by a computer. See Fig. 5 for an example of two such objects. Each trial will begin with the word "READY" on the screen; the participant will press a key that will erase the word "Ready" and present two objects. Participants will be instructed to respond (by pressing either a "yes" key or a "no" key) as quickly and as accurately as possible, deciding whether the two objects are the same or not. Four degrees of angular disparity between the two objects will be used. Half the trials will contain objects that are the same; half will contain objects that are mirror images of each other. Both response times and error rates will be recorded. Because prior work [12] has shown that response times increase as the degree of angular disparity increases, several measures will be taken including the slope and y-intercept for the best fitting straight line over the four levels of angular disparity and the overall mean response time on both "yes" and "no" trials. Each of these measures, along with appropriate error rates will be collected before and after the intervention with the PMR device and subjected to repeated measures t-tests.

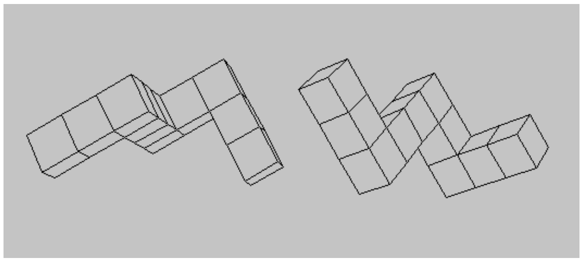

Figure 5. Example of mirror objects from Shepard and Metzler [12].

Participants will be given the Kolb's Learning Style Inventory [20] prior to the study and a questionnaire to assess their self-concept and self-efficacy related to key engineering visualization tasks both before and after the intervention with the PMR. The information from this questionnaire and their learning style will be quantified so that each measure can be used as a predictor variable in a series of multiple regression analyses on the pre- and post-intervention measures obtained from the response time studies and the spatial ability tests. Significant predictors will also be used as covariates in the repeated measures t-test. Also, from the information obtained through the self-concept and self-efficacy questionnaire, a series of repeated measures t-tests, regression analyses, cluster analyses, and factor analyses will be conducted to assess changes in self-confidence of spatial ability and attitudes toward engineering as a function of the intervention with the PMR.

V. Conclusions

Despite the emerging high technology economy in the United States and the world, a shortage of engineers currently exists and continues to grow. To address this deficiency in the high tech workforce, both the retention and attraction of students into engineering disciplines is required. One of the essential skills of a successful engineer is strong spatial ability. For example, the ability to correctly visualize three dimensional objects when they are represented in two dimensions, such as in CAD software or in a detailed part drawing, is a vital spatial skill in engineering. Research has shown that the spatial ability of engineering students can be improved through training with a CAD software package and also that students prefer working with actual physical objects when developing these spatial ability skills. However, whether the integration of an actual physical model with the CAD software can generate even greater advances in spatial ability compared to CAD software training alone, and whether similar spatial ability improvements can be achieved in a non-engineering population has not been investigated.

In this paper, a CAD integrated Physical Model Rotator device was proposed which will allow an actual physical object to rotate in unison with the same computer model in the CAD software.

The premise is that this physical model will assist the user in making the connection between the 3D object and its 2D representation on the computer screen. Details regarding the initial design of the Physical Model Rotator were presented. Also, subsequent testing methods to evaluate the effectiveness of an intervention with the Physical Model Rotator were outlined. These experiments will utilize standard Psychology tests for spatial ability assessment. If shown to be effective, this educational tool could be used to attract high school and non-engineering students to engineering fields due to the improved motivation and self-confidence the individuals will feel with respect to this essential engineering skill and for retention purposes in introductory design engineering courses where students may become discouraged due to their poor spatial ability. While this work is proposed with respect to improving retention and recruitment to engineering fields, this device could be used in other math and science disciplines which require strong spatial ability skills, for example molecular chemistry and architecture.

VI. Acknowledgements

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VII. References

1. National Science Foundation, *U.S. Science and Engineering in a Changing World*, Arlington, VA, 1996, NSF-96.
2. National Science Board, *Science and Engineering Indicators – 1996*, Washington, D.C., 1996, NSB-96.
3. Bishop J., "Developing Students' Spatial Ability", *The Science Teacher*, vol. 45, 1978, pp. 20-3.
4. Sorby, S. and B. Baartmans, "The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students", *Journal of Engineering Education*, July, 2000, pp. 301-7.
5. Hsi, S., M. Linn, and J. Bell "The Role of Spatial Reasoning in Engineering and the Design of Spatial Instruction", *Journal of Engineering Education*, April, 1997, pp. 151-8.
6. Pleck, M., "Visual Literacy – An Important Aspect of Engineering Design", Proceedings, 1991 ASEE Annual Conference, ASEE, 1991, pp. 1732-4Pleck, M., "Visual Literacy – An Important Aspect of Engineering Design", *Proceedings of the 1991 ASEE Annual Conference*, ASEE, 1991, pp. 1732-4.
7. Peters, M., P. Chisholm, and B. Laeng, "Spatial Ability, Student Gender, and Academic Performance", *Journal of Engineering Education*, Jan., 1995, pp. 1-5.

8. Miller, C., “Enhancing Visual Literacy of Engineering Students Through the Use of Real and Computer Generated Models”, Engineering Design and Graphics Journal, vol. 56, no. 1, 1992, pp. 27-38.
9. Henderson, K., *On Line and On Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering*, MIT Press, Cambridge, MA, 1999.
10. Ferguson, E., *Engineering and the Mind’s Eye*, MIT Press, Cambridge, MA, 1992.
11. Vandenberg, S. and A. Kuse, “Mental Rotations, A Group Test of Three-Dimensional Spatial Visualization”, *Perceptual and Motor Skills*, vol. 47, 1978, pp. 599-604.
12. Shepard, R. and D. Metzler, “Mental Rotation: Effects of Dimensionality of Objects and Type of Tasks”, *Journal of Experimental Psychology: Human Perception and Performance*, vol. 14, 1978, pp. 3-11.
13. Pintrich, P.R., and D.H. Schunk, *Motivation in Education: Theory, Research and Application* (2nd Ed.) Upper Saddle River, NJ, Merrill Prentice Hall, 2002.
14. Schunk, D.H., Self-efficacy and Academic Motivation, *Educational Psychologist*, Vol. 26, pp. 207-231.
15. Eccles J. and A. Wigfield, “Teacher Expectancies and Student Motivation”, in J.B. Dusek (Ed.) Teacher Expectancies, Hillsdale, NJ: Erlbaum, 1985, pp. 185-226.
16. Bandura, A., “Self-efficacy: Toward a Unified Theory of Behavioral Change”, *Psychological Review*, Vol. 84, 1977, pp. 191-215.
17. Bandura A., “Self-efficacy Mechanism in Human Agency”, *American Psychologist*, Vol. 37, 1982, pp. 122-147.
18. Pintrich, P.R. and E. De Groot, “Motivational and Self-regulated Learning Components of Classroom Academic Performance”, *Journal of Educational Psychology*, Vol. 82, 1990, pp. 33-40.
19. personal correspondence with Robert McGill, Manager Solid Partners Program, Solidworks Corporation, Jan. 2, 2001.
20. Kolb, D.A., *Experiential Learning: Experience as the Source of Learning and Development*, Prentice-Hall, Englewood Cliffs, NJ, 1984.

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