Communicating Advanced Manufacturing Concepts to Middle-school Students Using Lego-machines (Work in Progress)

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Dr. Samuel has been serving as an assistant professor in the mechanical, aerospace and nuclear engineering department of Rensselaer Polytechnic Institute, since the spring of 2011. As director of the Nano/Micro-scale Manufacturing and Material Design Lab at Rensselaer, he leads research and education efforts in the areas of advanced manufacturing and material design. Besides research, Johnson is also passionate about training and developing the next generation of manufacturing engineers in the US. He is the 2014 recipient of the National Science Foundation CAREER Award and the Rensselaer Class of 1951 Outstanding Teaching Development award.

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1. Introduction

In 2011, the President's Council of Advisors on Science and Technology (PCAST) identified advanced manufacturing as a key sector for revitalizing the economy and for promoting a culture of innovation in the United States (US) [1]. Following this, several federal programs and initiatives, such as the Advanced Manufacturing Partnership (AMP) and the National Network for Manufacturing Innovation (NNMI), have been announced to promote manufacturing research, education and jobs in the US [2-5]. While these steps are geared towards enabling a "manufacturing renaissance" in the Nation, the high-tech manufacturing sector is faced with a serious shortage of a skilled workforce [6]. This problem is further compounded by the fact that the youth in the country have a negative perception of the manufacturing industry and are therefore reluctant to pursue education and career opportunities offered by the field [7]. In order to address this national crisis, there is a critical need to develop innovative education and outreach programs for K-12 students that promote a healthy picture of manufacturing in the United States.

In this paper, we report the design and implementation of an advanced manufacturing educational module that uses Lego^{TM}-machines to teach critical manufacturing concepts to middle-school students (ages 12-14). The module comprises of a hands-on "design-and-build" exercise that allows the students to build a three-axis motion platform using Lego^{TM} components. This versatile motion platform is then used by the students to experience five advanced manufacturing-related concepts, viz., 1) The engineering-thought process that is required to construct a complex assembly of controllers, gear trains, and Lego^{TM} bricks; 2) The "art-to-part" creative process that transforms an idea into a tangible product; 3) The ability to quantify the 3-D space using coordinates that dictate the movements of the Lego^{TM} machine in space, 4) Cutting tool selection principles that dictate the trade-off between amount of material removed and resolution of final product, and 5) Tolerances and measurements through the use of a metrology end effector. The preliminary assessment data reveals that module has a positive impact on middle-school students.

The remainder of this paper is organized as follows. Section 2 presents the design and software implementation of two Lego^{TM}-based machine tools focused on subtractive manufacturing (machining) and metrology and Section 3 presents some of the advanced manufacturing concepts that can be conveyed using these machines. Section 4 discusses the Phase-1 implementation of these modules as part of a one hour in-class activity to middle-school students, followed by Section 5, which outlines on-going activities in the area of curriculum development and K-12 teacher training programs. Finally, Section 6 presents the specific conclusions that can be drawn from this work.

2. Lego^{TM}-based Machine Tools (LMTs): Design and Implementation

Over the past decade there has been significant research and development work done in the area of micro/meso-scale manufacturing in the United States [8]. Examples of this technology include portable micro-factories, micro-scale machining processes (micro-milling/drilling/turning etc.), and micro-scale metrology practices [8]. The modular nature of the Lego^{TM} units makes them well-suited to convey this technology-space to a middle-school student audience. Two Lego™-based machine tools (LMTs) capable of performing subtractive manufacturing (i.e., machining) and metrology operations were designed and built for our outreach activities. This section provides both the hardware as well as software implementation details for those two units. It should be noted here that similar design and build principles can be used to build LMTs for additive manufacturing (i.e., 3D printing) as demonstrated by Almodovar et al. [9]

2.1 Subtractive Manufacturing Machine Tool

Figure 1 depicts the overall construction and layout of the LMT used to demonstrate subtractive manufacturing (i.e., machining). The specifications of the machine are listed in Table 1. A three-axis, gantry configuration was used to create this machine since it is a commonly used design configuration both for macro and micro-scale machine tools [8]. The motion axes were programmed as per the coordinate system shown at the lower left hand side of Fig. 1. The machine is comprised of four sub-assemblies, viz., 1) Z-stage motor base; 2) Table; 3) X-stage gear rack and carriage; and 4) Y-stage gear-rack and carriage. More information on the construction of this subtractive manufacturing tool can be found at the following link: http://www.johnsonsamuel.com/outreach.html

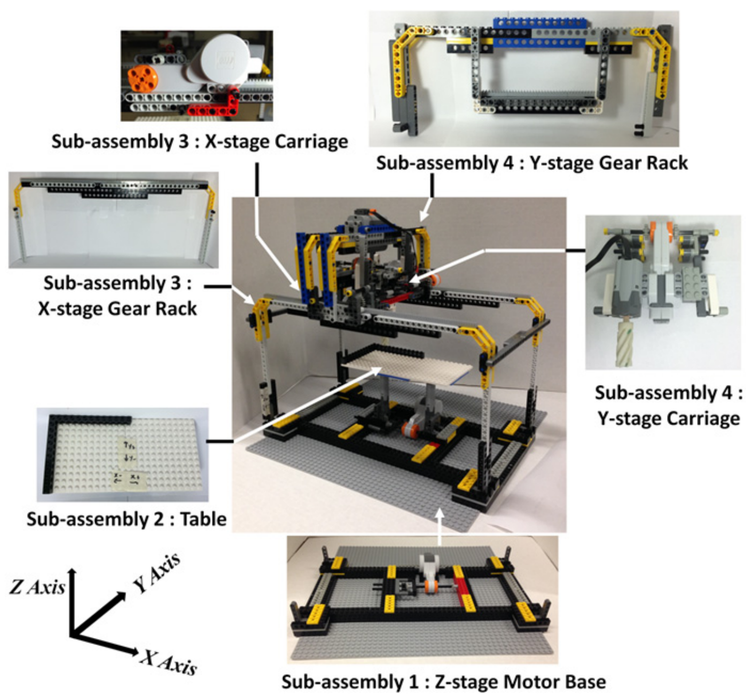


Fig. 1: Exploded View of Lego™-based machine tool (LMT) for subtractive manufacturing

Table 1: Machine specifications of Lego™-based machine tool (LMT)

X Axis Travel	~30 cm
Y Axis Travel	~15 cm
Z Axis Travel	~10 cm
X Axis Resolution	~4 mm
Y Axis Resolution	~4 mm
Z Axis Resolution	~1 mm
Spindle Speed	300 RPM (Clockwise or Counter-Clockwise)
Volume of Machine	38 cm x 38 cm x 38 cm

2.1.1 Software Integration to Enable Maximum Student Participation

The program code to run the subtractive manufacturing LMT is written in the open-source Lego™ Mindstorms NXT 2.0 software. Figure 2 shows the program flowchart that is used to control all axes of the machine. As seen in Fig. 2, the program involves three nested loops, each of which has a switch option that controls the direction of motion for a specific axis. As the students press specific controller buttons, the switch executes the command to either rotate the motor clockwise or counter clockwise. This nested loop implementation ensures that there is greater hands-on student participation during the programs since it requires one student to control each axis, (i.e., a total of three students) to operate the machine.

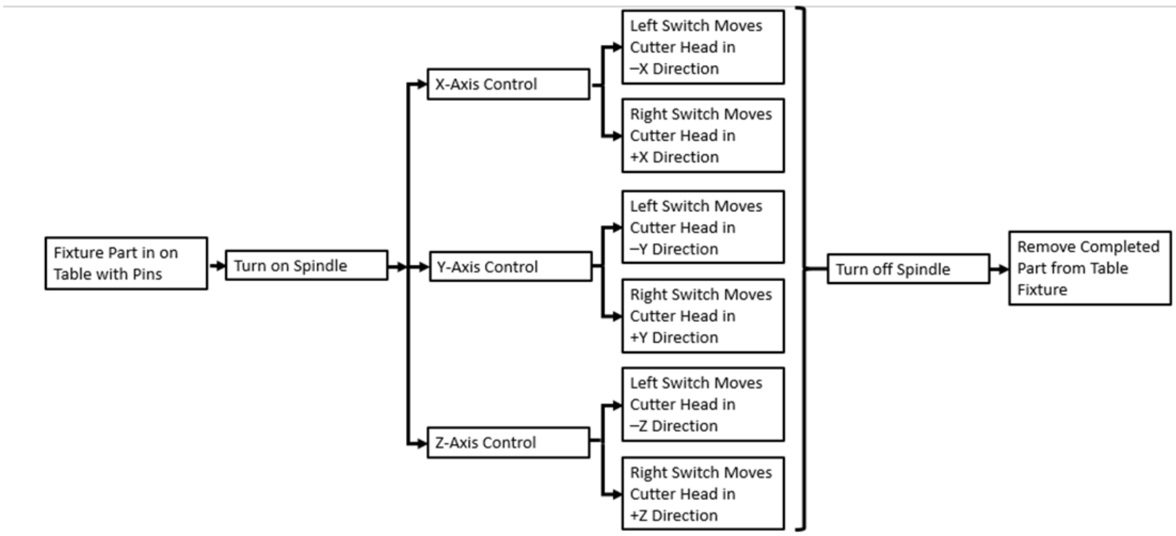


Fig. 2: Subtractive manufacturing (machining) machine tool program flowchart

2.2 Metrology Machine

In order to explain the concept of modularity, the metrology machine was designed such that the spindle of the milling machine could be swapped for a metrology head and the same LMT described in Section 2.1 could now be programmed to do metrology operations.

2.2.1 Design of Metrology Head

The metrology machine was designed to replicate the coordinate measurement machine (CMM) that is widely used in industry. Figure 3 shows the metrology head modification used on the LMT described in Section 2.1. Instead of the spindle motor used for the subtractive manufacturing machine, a touch sensor is mounted to the Y-stage carriage. At the end of the touch sensor, a Lego™ axle is mounted to replicate the probe that is used on CMM machines. The touch sensor is then plugged into the input of the Lego Mindstorms™ controller.

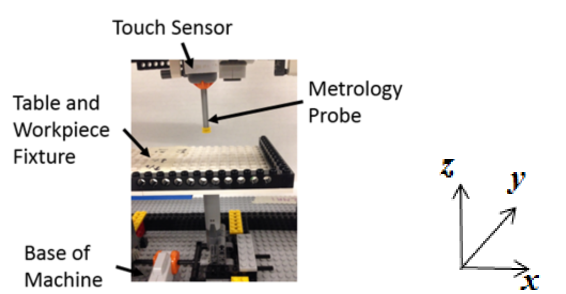


Fig. 3: Metrology head modification to Lego™ 3-axis machine tool

2.2.2 Software Integration to Enable Maximum Student Participation

Figure 4 depicts the overall process flow-chart for the use of the metrology unit. As seen the workpiece to be measured (in this case a plastic annular ring) is mounted on the table sub-assembly in Fig. 1. The touch sensor is then programmed to do a series of touch-scans on the workpiece. The coordinate locations of those scans are then used to plot the profile of the part being measured. Size-scale measurements can then be made off those plots.

Two different software packages were integrated to effectively collect the metrology data. The first was the Lego^{TM} Mindstorms NXT 2.0 software that was used to control the motion profile of the probe and to collect the data points. The second was the use of Matlab^{TM} to plot the data points in order to provide visual feedback to the students about the measurements that they made. It should be noted here that while Matlab^{TM} was used in our application, the plotting could also be done using common programs such as Microsoft Excel^{TM}.

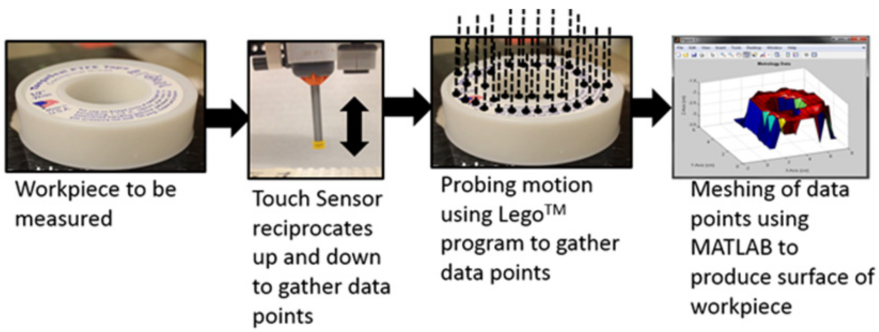


Fig. 4: Metrology process flow-chart

3. Advanced Manufacturing Concepts for Middle & High-school Students

Depending on the age-group of the students involved in the outreach program, the subtractive manufacturing and metrology units outlined in Section 2 can be used in multiple ways to communicate advanced manufacturing concepts. Some of these concepts are presented below along with the age-group of the students for whom it may be best-suited.

3.1 Engineering Thought Process (high-school students)

Building a complex assembly, such as the three-axis LMT, requires an engineering thought process and problem-solving skills. For older age groups (8-12th grade students), the module can be focused on the assembly/building of the Lego-based machine tools. This will enable the students to learn multiple concepts including techniques to constrain a component in three-dimensional space, the application of simple machines, and the software programming skills needed to control a set of hardware components (such as the motors and sensors).

3.2 Art-to-Part Creative Process (middle-school students)

The LMTs allow the students to experience the “art-to-part” design and manufacturing process (Fig. 5). The students can be taken on a guided exercise to develop certain 2D designs (“art”) that they would like to manufacture (“part”). Once these have been finalized, the students can be taught how to achieve that design using a series of machining operations. This step involves tool-path planning techniques and finally, the students get to operate the machine themselves to manufacture the part that they conceived. This tangible final product "rewards" the students for their efforts and reinforces their creativity.

Fig. 5: Art-to-part demonstration accomplished by the module

3.3 Quantifying 3D Space (middle-school students)

The machine tool moves in three dimensional space to remove material in a designated location. This requires students to be able to relate the movement of the machine tool to each axis of the machine. Students learn to apply the concepts learned in geometry to be able to move the machine to the location and orientation they desire (Fig. 6).

3.4 Cutting Tool Selection Principles (middle-school students)

Based on the material and geometry being machined, the industry uses different cutting tools. These tools vary from small endmills and drills to large shell endmills. These LMTs allow students to learn the trade-offs between using large and small cutting tools, i.e., large cutting tools are able to remove large amounts of material quickly, whereas the opposite is true for smaller tools.

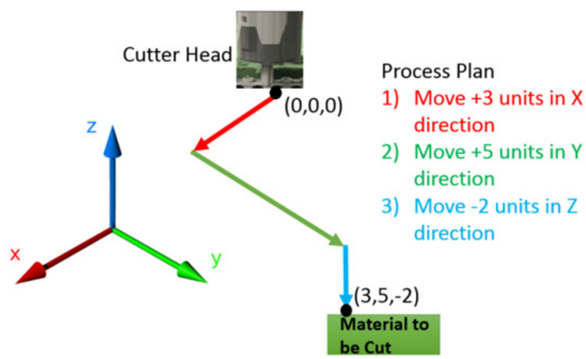


Fig. 6: Image used to quantify 3-D space to audience during module

3.5 Tolerances and Measurements (middle-school & high-school students)

The metrology module provides a pathway for students to develop a better understanding of the tolerances associated in the manufacturing industry. By exposing the students to the length-scale present in advanced manufacturing processes, the topic of tolerances can also be discussed in terms of the tradeoffs that exist between the costs and process accuracy. For the high-school students, the metrology exercise can be modified to investigate the impact of probe stiffness and geometry on the accuracy of the metrology measurements.

4. Phase-1 Implementation: Middle-School In-class Activity

In order to evaluate the efficacy of the Lego™-based modules, the Phase-1 implementation of our outreach efforts was focused on developing a 1 hour in-class activity for middle-school students. The format of the activity included a dynamic presentation that conveys the manufacturing concepts, followed by a hands-on activity that takes them through the art-to-part process, quantifying the 3D space, and cutting tool selection principles. Figure 7 depicts the overall structure of the module. Figures 8 are images taken from school visits showing students completing the hands-on activity of the module.

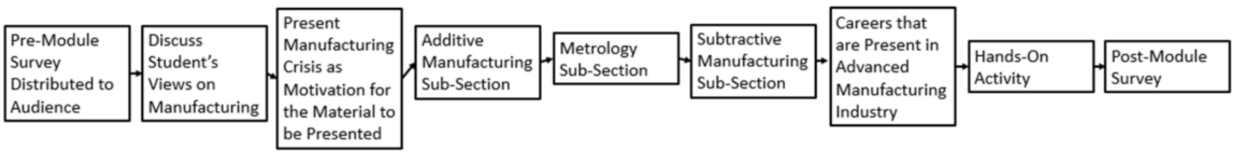


Fig. 7: Phase 1 – Outreach module flow-chart

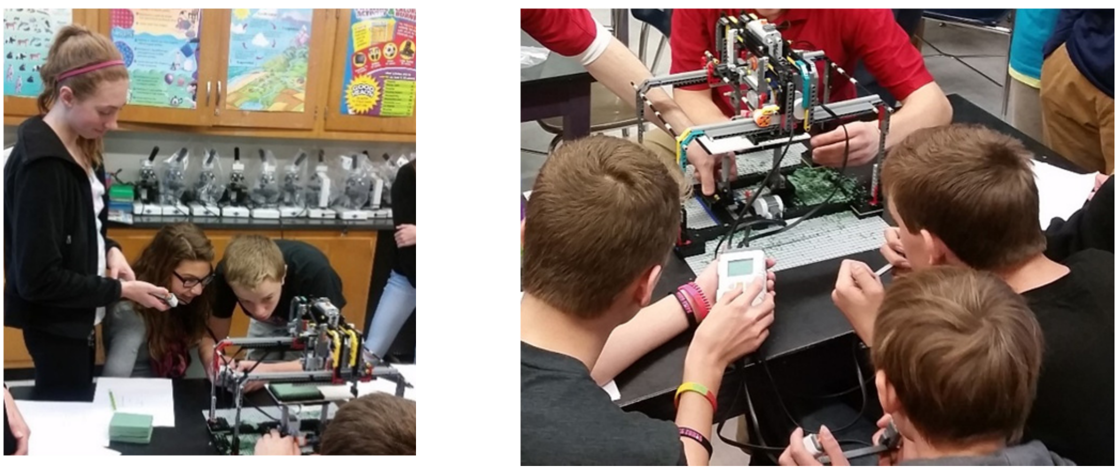


Fig. 8: Middle students engaging in hands-on activity of module

4.1 Assertion Evidence-based Module Presentation

It was important to be creative in both the content and the presentation of the educational content, since students exposure to technical sciences varied. Furthermore, since the aim is to keep the students upbeat and excited about what they are learning, the presentation is built around the use of technology, hands-on activities, and active participation. Rather than using the conventional PowerPoint-based presentation, the authors used an assertion-evidence method of presentation [10], which has been shown to result in greater audience retention rates. This method minimizes the use of words and uses images, videos and the oral delivery to convey the content of a technical presentation. The contents of this presentation can be found at the following link: http://www.johnsonsamuel.com/outreach.html

4.2 Assessment Data

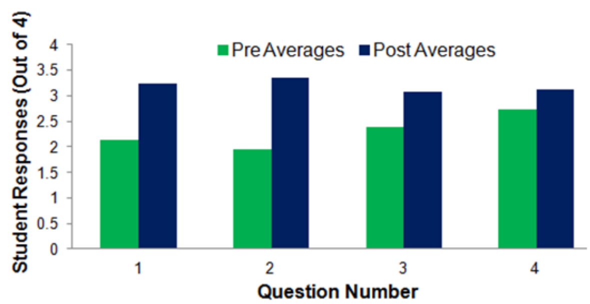
The presentation and hands-on activity were designed to occupy a one-hour class period. The first half of the period was devoted to introducing manufacturing concepts, while the second half was devoted to students working on the Lego™ 3-axis milling machine. For one school visit, a total of 49 valid sets of pre- and post-module surveys were collected. As seen in the table below, the four questions in our Institute Review Board approved survey (Fig. 9a) were aimed at four key response categories:

1) **Career Awareness**, i.e., their knowledge of possible advanced manufacturing careers
2) **Crisis Awareness**, i.e., their awareness of the human resource crisis facing the nation in the area of advanced manufacturing.
3) **Interest in Manufacturing Industry**, and
4) **Continued Learning,** i.e., their interest in continued learning of advanced manufacturing

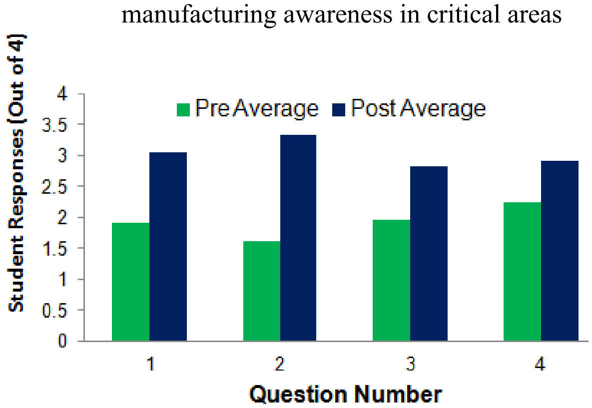
Figure 9b presents the average data obtained for each of the four question categories. The data from this graph shows that after the exposure to the module, the students exhibited an improvement across all four key categories. Figure 9c-d depicts the same data, but now separated according to gender-specific responses. It is interesting to note that the modules were more effective with the female students. While the reasons for this are not clear, the results point to the fact that the modules are effective in increasing the interest of women in manufacturing.

	Scale			
	Strongly Agree/High	Agree	Disagree	Strongly Disagree/Low
Question	4	3	2	1
1) What is your level of awareness about careers in manufacturing and nanoscale technologies?	CAREER AWARENESS			
2) What is your level of awareness about the manufacturing crisis facing America today?	CRISIS AWARENESS			
3) Would you find it interesting to work in the manufacturing industry?	INTEREST IN MANUFACTURING INDUSTRY			
4) Are you interested in learning more about manufacturing (through a class, job, etc.)?	CONTINUED LEARNING			

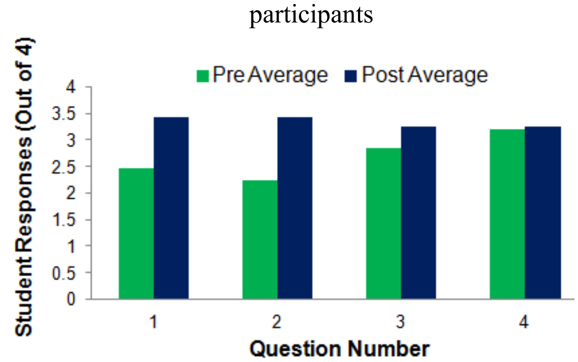
(a) Survey questions used to asses student's manufacturing awareness in critical areas



(b) Average responses of survey questions for all participants



(c) Female student responses



(d) Male student responses

Fig. 9: Pre- and post-module responses for questions 1-4 [Note: (Q1) Career awareness, (Q2) Manufacturing crisis awareness, (Q3) Interest in manufacturing industry, (Q4) Continued learning

In addition to the above four questions, the students were also asked to identify three key words that they would connect with the manufacturing industry. Out of the ten available words, half of the available words were deemed to represent a negative perception of manufacturing, while the other half were representative of positive views about advanced manufacturing. Figures 10 a-b

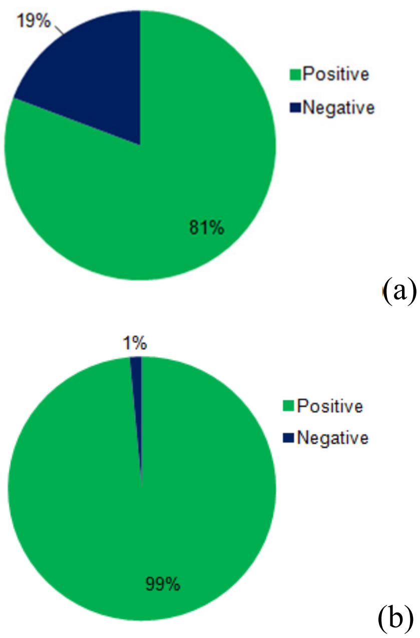


Fig. 10 : Positive/negative word association with manufacturing (a) Pre-module (b) Post-module

show that the overwhelming majority of students had all positive views on manufacturing after the module.

5. Phase-2 Efforts: Curriculum Development and Teacher Training Efforts (On-going)

Given the initial success of the 1 hour in-class module, there are on-going efforts to develop an outreach curriculum around these LMT units and to also train middle-school teachers in the design, building and testing of LMTs. These efforts are aimed at ensuring wide-spread dissemination of these Lego^{TM}-based manufacturing education modules. Our team is also currently working closely with local middle-school and high-school teachers to develop a Lego^{TM}-based curriculum for manufacturing outreach. The efforts are focused on developing preliminary lesson plans that meet the New York state educational standards for science and technology courses. This course curriculum will start by explaining the concepts of simple machines and evolve to allow teams of students to build the 3 axis LMT similar to the one described in Section 2.

6. Conclusions

The following conclusions can be drawn from the work presented in this paper:

1. Lego-based machines are an appropriate medium to convey micro/meso-scale manufacturing concepts to middle-school and high-school students. The interactive nature of the in-class modules developed around Lego^{TM} units makes them appealing to be used by K-12 teachers across the nation to convey advanced manufacturing concepts.
2. Two Lego^{TM}-based machine tools have been designed and implemented, viz., a subtractive manufacturing unit and a contact-based metrology unit. The software implementation on both these units is designed to facilitate hands-on student participation. These units can be used to communicate concepts such as the engineering thought process, art-to-part creative process, 3D space quantification, cutting tool selection principles, and tolerances in a manufactured part.
3. The Phase-1 implementation of the Lego^{TM}-based outreach module consisted of an in-class activity for middle-school students. This involved both an assertion-evidence-based presentation as well as a hands-on activity that took the students through the art-to-part process. The assessment data reveals that the modules are making a positive impact on the students including the female demographic.
4. Given the initial success of the 1 hour in-class module, there are on-going efforts to develop an outreach curriculum around these Lego^{TM} units and to train middle-school

teachers in the design and testing of these Lego™ units. These efforts are aimed at a wide-spread dissemination of these modules.

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