# Enabling Machine Design Innovation among Freshman Mechanical Engineering Students

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Dr. Purwar received his Ph.D. from State University of New York at Stony Brook and his B. Tech from IIT Kanpur, both in Mechanical Engineering. His research interests are in machine design area with a focus on kinematic design of robots and mechanisms, CAD/CAM, and application of Computational Geometry, Virtual Reality (VR), Computer Graphics and Visualization in Design Engineering.

Dr. Purwar's research work has been published in several international journals and conferences and he is the recipient of the Presidential Award for Excellence in Teaching by Stony Brook University. His research has been funded by National Science Foundation (NSF), NY-state SPIR, -Center for BioTechnology, -SensorCAT, SUNY Research Foundation, SUNY Office of Provost, and numerous industry partners. His work on the interactive dimensional synthesis of planar 6R mechanisms won him a best paper award at the 2009 ASME International Design Engineering Technical Conferences (IDETC).

He has been twice elected as a member of the ASME Mechanisms and Robotics committee and served as the Program Chair for the 2014 ASME Mechanisms and Robotics Conference, as the Conference Chair for the 2015 ASME Mechanisms and Robotics Conference and has served as symposium and session chairs for many ASME International Design Engineering Technical Conferences. He is the general Conference Co-Chair for the 2016 ASME International Design Engineering Technical Conferences (IDETC/CIE).

Dr. Purwar is also the department's representative to the NY state-funded Strategic Partnership for Industrial Resurgence (SPIR) program. As the SPIR representative, he identifies and coordinates projects between the department and Long Island based industries. SPIR projects include joint proposals for federal funding, manufacturing and quality assurance improvements, research and development, and testing and evaluation.

He won a SUNY Research Foundation Technology Accelerator Fund (TAF) award, which enabled him to develop a multifunctional Sit-to-Stand-Walker assistive device for people afflicted with neuromuscular degenrative diseases or disability. The technology and the patent behind the device has been licensed to Biodex Medical Systems for bringing the device to institutional market. See Governor Cuomo's announcement at http://www.governor.ny.gov/press/10012013-biodex-medical-systems.

Dr. Purwar gave an invited TEDx talk on Machine Design Innovation through Technology and Education (available athttp://youtu.be/B4VfrtHNJtY?t=44s), which focused on enabling democratization of design capabilities, much needed for invention and innovation of machines by uniting the teaching of scientific and engineering principles with the new tools of technology.

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## 1 Introduction

This paper presents 1) creation and teaching of a newly developed *Freshman Design Innovation* (FDI) class for Mechanical Engineering students at Stony Brook University (SBU), and 2) *MotionGen*, a Mechanism Design app for iOS and Android platforms developed indigenously and incorporated in this class as a technology enabler (Fig 1). The MotionGen enables students to perform kinematic design of planar four-bar linkage mechanisms that can execute desired paths or motions.

In the recent years, Engineering educators have mandated an introduction of design concepts, innovation, entrepreneurship, and projects early in a student's education, promote teamwork, and introduce modern engineering tools. The National Academy of Engineer's "The Engineer of 2020" report concludes that the passive, lecture-based instruction should be replaced or supplemented by active, integrated, project-based learning with significant design component.[2,3] It is not uncommon to see various academic institutions introducing design and innovations early in the curriculum.[4–10] Arce et al.[11] emphasize preparing and educating engineers who can excel in a creativity- and innovation-based economy.

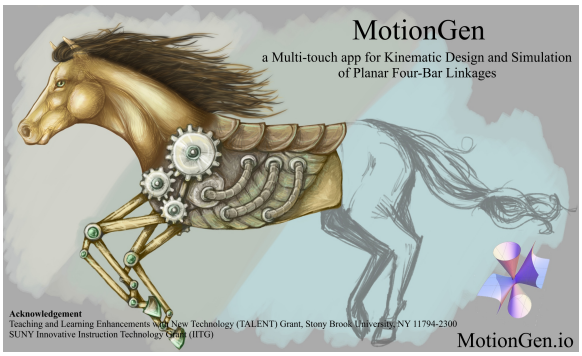



Figure 1: The About Screen of MotionGen

Almost concurrently, we have seen a renaissance of maker movement, hobby shops, and economically successful trends enabled by democratization of manufacturing tools (3D printers, laser cutters, and service bureaus), open-source software and hardware, and crowd-funding platforms. These trends have set up a perfect playground for engineering students to learn Engineering concepts and acquire valuable skills in a fun-filled, design-oriented context and eventually learn how to innovate and invent machines. However, this goal would remain unfulfilled unless there is a corresponding democratization of design capabilities.

Design, prototyping, and programming of robots and machines, even at a small scale, provides a perfect platform for Engineers to learn the basics of many disciplines of Engineering. Design of machines typically begins with generation, evaluation, and analysis of mechanism design concepts that can realize a given task. Lack of a systematic theory and simple, intuitive tools that allow both novice and experienced designers to design mechanisms for machine design applications has made achieving this goal difficult. However, the recent work of the author in Machine Design area and the use of intuitive multi-touch devices like iPads have the potential to be powerful enabler of design innovations. In fact, the touch-based interaction provided by these devices, albeit imprecise, affords greater flexibility and versatility in design over traditional desktop metaphor. Use of mobile-apps and -devices equipped with sensors are poised to usher education into a new realm of hands-on, flexible, and always-available learning.[12,13] The current literature indicates that the mobile technologies in education are serving as educational sandbox and removing the artificial boundaries between learning and playing while providing more time for hands-on activities that enhance student's cognition.[14,15]

We have implemented our latest algorithms to develop MotionGen, an app for designing planar four-bar linkage mechanisms and also created a new Freshman Design Innovation class that revolves around teaching and enabling freshman students to innovate mechanical devices by designing mechanisms using the app, assembling them into a 3D printed or laser-cut robot chassis, and finally programming them using a take-home Microcontroller Mechatronics kit. This paper presents the details of this class and the app and shows how Engineering Educators could benefit from the resources developed by the author.

The rest of the paper is organized as follows: in Section 2, we present MotionGen and summarize its essential functions; in Section 3, we present the motivation, mission, goals, and Course Learning Objectives of the new Freshman Design Innovation class; in this section, the details of the Final Design project are also discussed. Finally, in Section 4, the Assessment part is discussed before concluding the paper.

# 2 Innovating Machines using MotionGen

In the machine design pipeline, the first stage is to generate mechanism design concepts that can fulfill the motion requirements of a machine. For example, an Internal Combustion engine's basic mechanism for converting piston's reciprocating motion to a rotary motion to be eventually transferred to the wheels is a well-known planar four-bar linkage called slider-crank mechanism. Although there are a few desktop software systems available that provide extensive simulation and analysis capabilities,[16–20] none provide true synthesis capabilities that would enable designers to innovate machines at a fundamental level. Autodesk's Force Effect Motion[21] is one of the few mobile app, which provides simulation capabilities for $N$-bar linkages. A detailed review of the state of the art in Computer Aided Mechanism Design can be found in Chase et al.[22] and is summarized in Purwar et al.[23]

MotionGen[24] (http://www.motiongen.io) is a planar four-bar linkage simulation and synthesis app available for download for free at both Google Play–[25] and Apple's iTunes–[26] Stores. An early version of the app was presented in Purwar et al.,[27] which details its functions and features. This app allows users to synthesize planar four-bar linkages by assembling two of the planar *RR*-, *RP*- and *PR*-dyad types, where *R* refers to revolute (or, hinge) and *P* refers to Prismatic (or, sliding) joints. The input task is a planar motion given as a set of discrete positions and orienta-

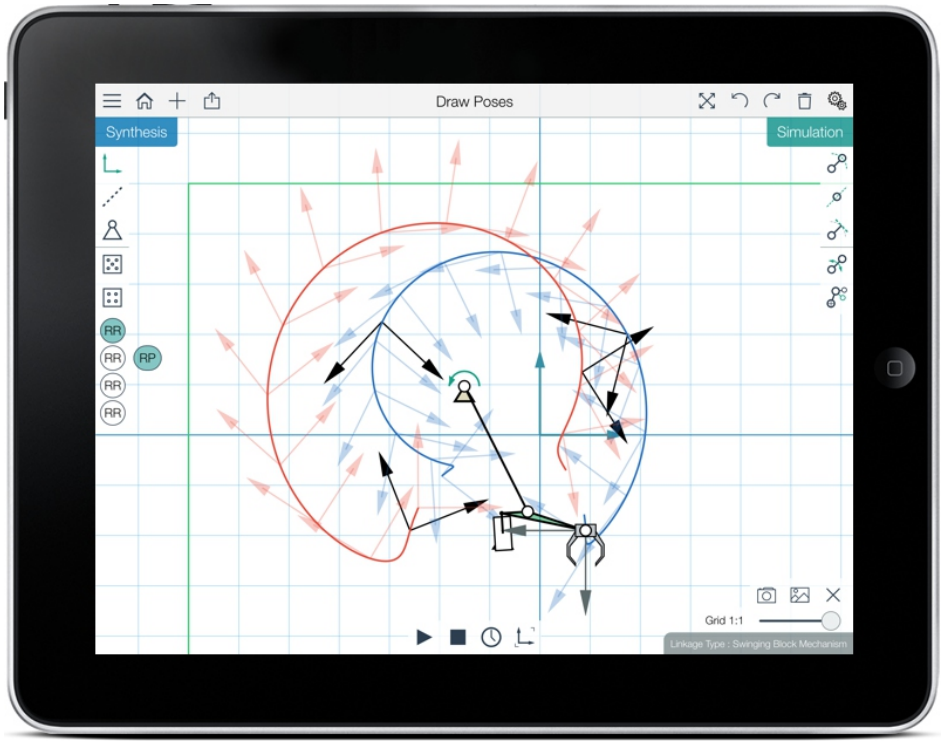



Figure 2: iOS version of the MotionGen app showing a four-bar linkage interpolating through five given positions; three *RR*- and one *RP*-dyads are computed.

tions (referred to as a pose, hereafter) and the app computes type- and dimensions of synthesized planar four-bar linkages, where their coupler interpolates through the given poses either exactly or approximately while minimizing an algebraic fitting error. The algorithm used in the app is an implementation of our simultaneous type and dimensional synthesis approach presented in Ge and Purwar,[28] Ge et al.[29,30] In essence, the algorithm extracts the geometric constraints (circular, fixed-line or line-tangent-to-a-circle) implicit in a given motion and matches them with corresponding mechanical dyad types enumerated earlier. In the process, the dimensions of the dyads are also computed. By picking two dyads at a time, a planar four-bar linkage is formed. Due to the degree of polynomial system created in the solution, up to a total of six four-bar linkages can be computed for a given motion. Figure 2 shows an example where five positions are input and the MotionGen computes four possible dyads.

MotionGen also lets users simulates planar four-bar linkages by assembling the constraints of planar dyads on a blank- or image-overlaid screen. This constraint-based simulation approach mirrors the synthesis approach and allows users to input simple geometric features (circles and lines) for assembly and animation. As an example of the Simulation capabilities of the app, Fig. 3 shows a walking robot driven by two sets of planar four-bar linkages where the foot approximately traces a trajectory of walking motion. The users can input two dyads on top of an imported image of a robot or machine to verify the motion and make interactive changes to the trajectories.

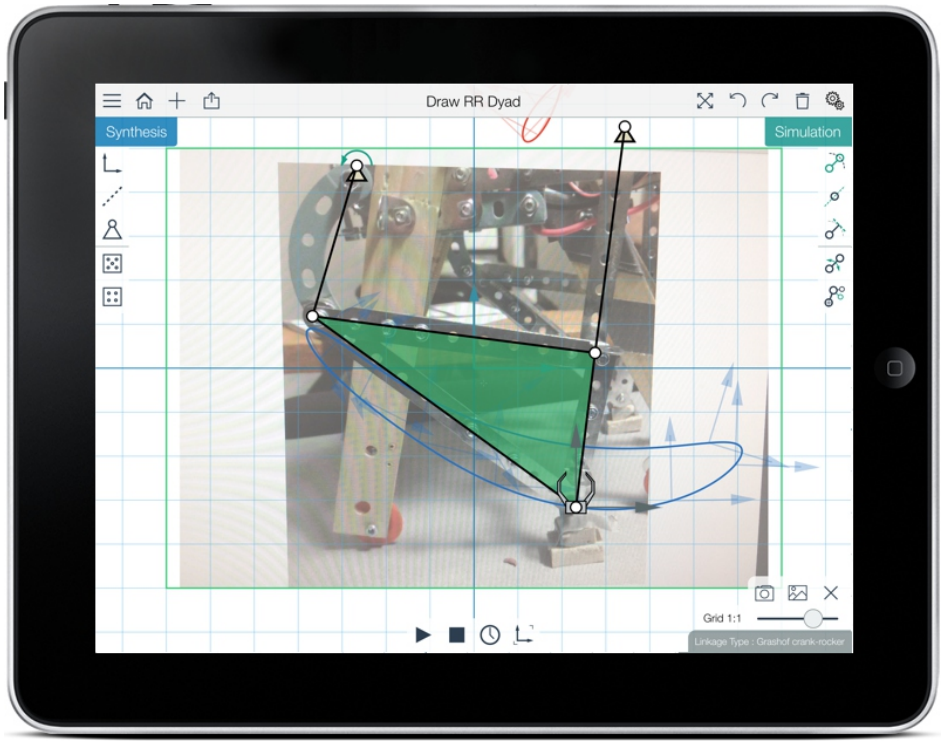



Figure 3: iOS version of the MotionGen app showing a four-bar linkage driving a walking robot designed and prototyped by the students in the author's *Freshman Design Innovation* class

# 3 Freshman Design Innovation

## 3.1 Motivation

Steve Jobs, Apples co-founder once said, "...everyone should learn how to program a computer because it teaches you how to think." More recently, Cognitive Scientists have shown that exercising motor control and physical manipulation leads to better meta- and embodied-cognition, which explore a confirmation or denial of what we know and how our coordinated hand movements enhance our thinking,[31,32] respectively. In light of these findings and low-cost availability and accessibility of manufacturing, computing, and electronics prototyping, it would make sense if we extended Jobs's quote to include learning how to design, build, and program a robot or machine. Genco et al.[33] assert that Freshman students, in general, are more creative and innovative than seniors. Therefore, it is especially important that freshman students are encouraged to design and innovate while they are not burdened with analysis-oriented classes.

## 3.2 Mission and Goals

Thus, making that as the practical context for a new three-credit Freshman Design Innovation class, we formulated the mission of the class "to excite the freshman Mechanical engineering students by the breadth of the offering in their engineering education while emphasizing learning the engineering principles in the context of design and in the spirit of maker culture." This course, required for all the Mechanical Engineering students at SBU, introduces students to the process of engineering design and provides a project-based design experience wherein the students design and

build a microcontroller driven autonomous mechatronic device. In doing so, they are provided an early exposure to the systematic approach to engineering problem solving that brings together fundamentals concepts of forces, motions, energy, materials, manufacturing processes, and machines and mechanisms. This goal aligns well with our department's vision to create a design-oriented paradigm of Mechanical Engineering education that begins with an early introduction to design principles and ends with capstone design experience.

Some of the Course Learning Objectives (CLOs) of this class pertaining to the design experience are:

1. Apply Engineering Design Process and Engineering Ethics to practical situations
2. Analyze simple structures and machines for Forces, Moments, and Stress and Strain
3. Compute Mechanical Energy, Work, and Power for basic machines
4. Articulate motions of the common mechanisms
5. Demonstrate an understanding of basic electronics and create circuit drawing
6. Demonstrate integration of sensors and actuators in circuits
7. Demonstrate Microcontroller programming using Arduino[34]
8. Design, fabricate, and program an autonomous, microcontroller-driven machine

## 3.3 Design Experience

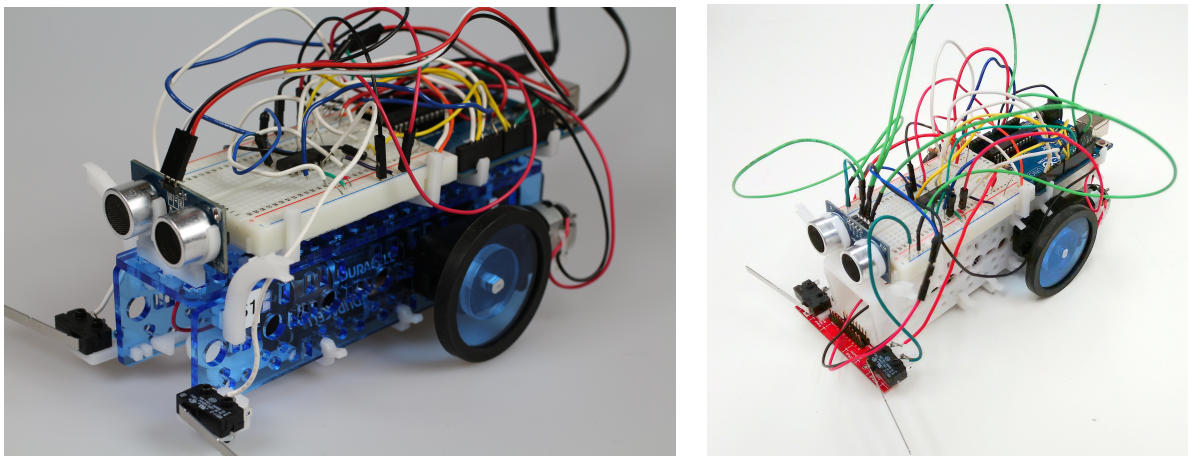
A highlight of the class is the final Design project, wherein the students have to design and build an autonomous robot/machine that either carries out either a functional or interesting motion. The goal is to motivate students to think about designing and prototyping programmable, electromechanical devices at an early stage of their engineering career. In doing so, they apply fundamentals to a fun and exciting design problem of their choice, learn to think critically, communicate ideas, and work in a team.

### Resources

Although, the aforementioned CLOs comprise of a fairly comprehensive range of topics seeking to prepare students for their final project, it would be naive to assume that at freshman level students can apply a basic knowledge of Statics, Kinematics, Dynamics, Strength of Materials, Design Methodology, Mechanisms and Machines, Sensors, Actuation, and Micro-controller programming to carry out a project of such complexity without any preparation. To assist students with this project, following resources and assistance were provided to the students:

1. **Robot Design Web site**: The author created a project web site https://sites.google.com/a/stonybrook.edu/mec101-robot-design-project-fall-2015/, which contains tutorials and helpful information about Arduino Programming, Sensors, Actuators, and other electronic and print resources.

2. **HWBot-An Experimental Platform**: It is imperative to provide an early design exposure to robot design and programming before expecting students to carry out a complex project. To this end, the author in the summer of 2015 designed a small two-wheel differential drive modular robot, called HWBot, made of laser-cut pieces that simply snap together; see Fig. 4. This robot was given to all the students in the class. The modular design ensures that the robot can be readily outfitted with a variety of off-the-shelf sensors (photocells, limit switches, passive Infra-red, line-tracking, ultrasonic), actuators (DC- and servo-motors), battery packs, breadboards, and micro-controller units.



(a) Acrylic HWBot (b) Delrin HWBot

Figure 4: These 2-wheel differential drive HWBots laser-cut in two different materials, Acrylic and Delrin, show ultrasonic sensor, limit switches, line-tracking sensor, Arduino, and breadboard assembled

The HWBot serves as an experimental platform for the students to carry out a series of interconnected HW assignments on programming basic motions, computing power and torque for a given kinematic performance, and ultimately adding behavior-based robotics capabilities using different sensors and actuators. In addition, they also learn how keeping the design modular with snap together pieces would enable them to design their own final project. We provided design files for the HWBot in AutoCAD Inventor to students so that they had a starting point for making their own designs for the project.

3. **Prototyping**: The scaled-down version of the machines and the planar linkages to drive them make them particularly amenable to manufacturing via 3D printing and laser cutting and keeping freshman students away from our machine shop. Prototyping a functional and nicer-looking machine or robot reinforces the practical design education goal, wherein, the emphasis is equally on the quality of the artifact and helping students understand and experience the process and methods of realizing an artifact. Our department currently supplies a Mechatronics project kit consisting of Arduino, motors, and other electronics along with a laser-cutter to cut their final project design.

4. **MotionGen**: Although, the design constraints and specific goals of the project are subject to change every year, the basics remain same, wherein an emphasis is placed on designing

complex motions. In that regards, the MotionGen helps students design planar four-bar linkages for their project. They begin by identifying the motion requirements of the problem: inputting just a few poses for the motion allows them to see synthesized planar four-bar linkages. The MotionGen also lets students specify fixed pivot points as well as lines along which fixed pivots should lie.

5. **Technical Advisers**: The author has successfully recruited past FDI class students as well as graduate students as Technical Advisers, who volunteer their time working with student teams to mentor and assist them in their project. This helps them reinforce their own understanding of engineering design, electronics, programming, and prototyping and derive the joy of helping their juniors.

# 4 Assessment

Since the MotionGen app became available on the stores in late last December, a formal assessment on the effectiveness of the app involving students has not been carried out yet. * However, the curriculum development for the FDI class began with SMART outcomes appropriate to the course topics and general education curriculum. Assessing outcomes related to the MotionGen app in learning machine design will be through homework, group projects, project designs and final product. These outcomes have traditionally been met in the junior and senior years, and this app will bring learning at the application and synthesis levels into the freshman and sophomore years. In terms of demonstrating overall learning effectiveness, senior design course outcomes can be compared with other sections taught by instructors with identical outcomes and design projects can be compared versus previous years' projects. The author anticipates that introduction of this app earlier in the curriculum will improve student success and design integration as the student reaches the senior design project.

In the course evaluations, the students have hailed the robot design experience as challenging, but the one that built their creative confidence and prepared them for life-long learning skills; see a few demo pictures from the Fall 2015 class in Fig. 5. The FDI class structures active-learning elements in a design- centric class wherein the students learn Mechanical Engineering principles, Electronics, and Programming in a more practical context. The accessible, fun, and exciting nature of this class make it an attractive choice for high school, freshmen students, and even adults out of college interested in engineering.

# 5 Conclusions

This paper presented MotionGen, an app for iOS and Android platforms, which solves the motion generation problem for planar four-bar linkages and a newly developed Freshman Design Innovation class that incorporates the app as a technology enabler for designing mechanism design concepts for mechatronic devices. The app provides students and machine designers a pathway to innovation and enables realization of the true benefits of the democratization of manufacturing and programmable electronics. The design experience in the class provides students an outlet for exercising their creativity at the highest level of Bloom's taxonomy.

*A web-based, private beta version was provided to students in the Fall 2015 to assist them with their projects.

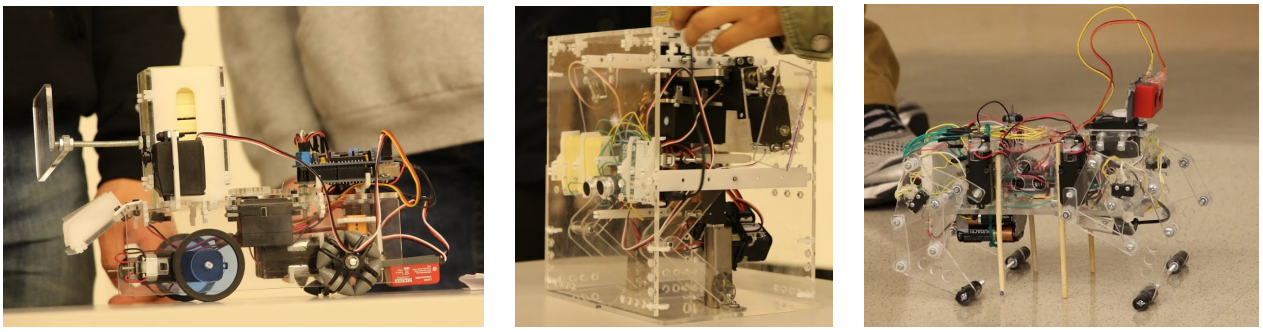


Figure 5: A few pictures of the projects from the Final Robot Design Project Demo day, Fall 2015; see complete gallery of pictures at https://goo.gl/photos/WhYmy4kxFoStwNQz7

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