Machine-Learning Driven Robot-Motion Design: Introducing a Web-Based Mechanism Design Software

Prof. Anurag Purwar, Stony Brook University

Dr. Anurag Purwar is an Assistant Professor in the Mechanical Engineering department at Stony Brook University. His research interests are in bringing together rigid body kinematics and machine learning for design of mechanisms and robots. He has published 82 peer-reviewed conference and journal papers and his research has been funded by National Science Foundation (NSF), NY-state SPIR, NY-state Center for Biotechnology, Sensor-CAT, SUNY Research Foundation, industry, Stony Brook University, and SUNY Office of Provost.

He received A.T. Yang award for the best paper in Theoretical Kinematics at the 2017 ASME Mechanisms and Robotics Conference and the MSC Software Simulation award for the best paper at the 2009 ASME International Design Engineering Technical Conferences (IDETC) . He is the recipient of the Presidential Award for Excellence in Teaching by Stony Brook University and the winner of the 2018 FACT2 award for Excellence in Instruction given to one professor from the entire SUNY system. He also received the 2021 Distinguished Teaching Award from the American Society of Engineering Education (ASEE) Mid-Atlantic Division.

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 was the general Conference Co-Chair for the 2016 ASME International Design Engineering Technical Conferences (IDETC/CIE).

He won a SUNY Research Foundation Technology Accelerator Fund (TAF) award, which enabled him to develop a multifunctional Sit-to-Stand-Walker assistive device (http://www.mobilityassist.net) for people afflicted with neuromuscular degenerative 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. The device won the SAE Top 100 Create the Future Award in 2016. Dr. Purwar gave a TEDx talk on Machine Design Innovation through Technology and Education (https://www.youtube.com/watch?v=iSW_G0nb11Q) 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. Five of his patented inventions have been successfully licensed to the companies world-wide.

Dr. Purwar is an elected member of the ASME Mechanisms and Robotics Committee and a senior member of the National Academy of Inventors (NAI). He is currently an Associate Editor of the ASME Journal of Computing and Information Science in Engineering and of International Journal of Mechanics Based Design of Structures and Machines.

Machine Learning Driven Robot Motion Design: Introducing a Web-based Mechanism Design Software

Abstract

This paper presents a novel machine-learning-driven web-based software, which enables the design and simulation of planar N-bar single and multi-degree-of-freedom linkage mechanisms for robotics and mechatronics applications. The software is developed using research methodologies to create a new computational framework for simultaneous type and dimensional synthesis of mechanisms for motion generation problems. The existing paradigm of selecting the type of a mechanism and then computing the dimension is shown to be inadequate in meeting the requirements of designers. Therefore, a new data-driven approach is proposed in which both the type and dimensions of a mechanism are computed directly from the user input, i.e., motion or path. While a formal assessment of the software in a classroom setting is pending, this paper outlines its broad applicability to support the learning outcomes of several mechanical engineering classes, from freshman engineering to advanced kinematics and robotics. The software has been adopted by numerous universities and organizations and was developed with funding from the National Science Foundation.

1 Raison d'être

The construction of machines and robots involves the utilization of one or more mechanisms to transmit or convert motions between interlinked parts. It is widely accepted that an inadequate selection and design of mechanisms in robots cannot be rectified by advanced electronics or computer programming. During his keynote address at the International Foundation of Robotics Research (IFRR) Colloquia in 2020, Prof. Shigeo Hiroshe spoke about the significance of mechanism design in robotics and emphasized that it is the foundation of a robot. He further mentioned that even if considerable efforts are devoted to other aspects, such as Artificial Intelligence (AI) in robots, they will be unsuccessful if the mechanical design aspect is overlooked [1]. However, designing mechanisms has often been deemed a combination of art and science, mainly due to the dearth of computational design tools and methods. Consequently, expertise and experience in mechanism design are prerequisites. Figure 1 depicts Watt's mechanism for a steam engine, which involves a four-bar mechanism in combination with a pantograph. The history of machines and mechanisms reveals that Watt took more pride in this mechanism than in the engine itself. After studying this relatively complicated mechanism, Franz Reuleaux, regarded as the father of modern kinematics, commented, “We appreciate the motives and some of the final results of Watt's endeavors, but we do not find any indication of a systematic sequence of ideas leading up to them." [2].

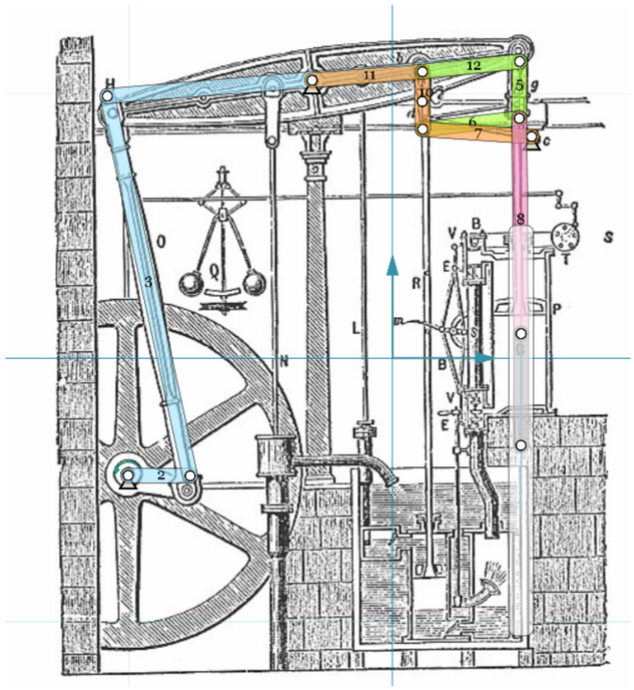
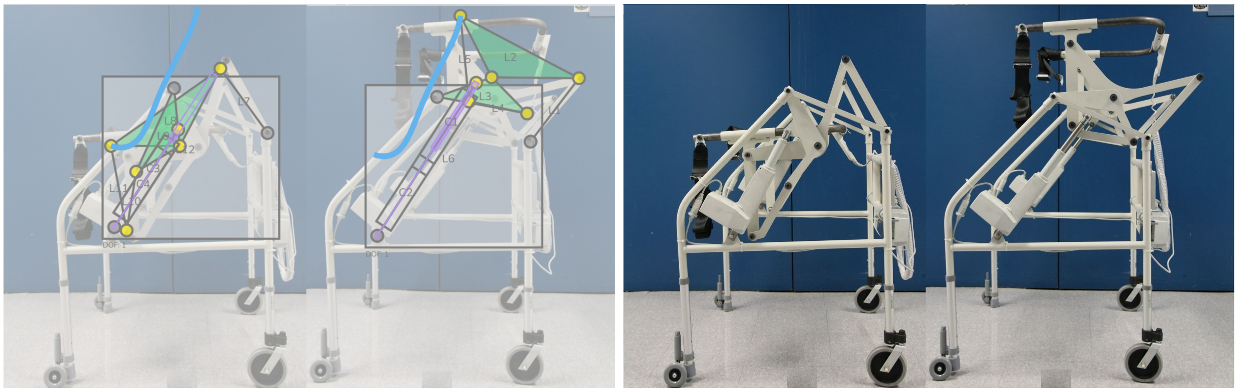


Figure 1: Watt's steam engine mechanism sketched in MotionGen Pro overlaid on a public domain drawing [3]; designed by Boulton and Watt, England, 1784

Following World War II, there was a significant surge in academic research on the use of digital computers to solve problems related to kinematic analysis and synthesis. However, despite several decades of research, the development of computational design tools for mechanism synthesis has been challenging. Most of the innovations in creating such tools have come from various academic research groups leading to software like LINCAGES [4, 5] KINSYN III [6], Kihonge et al. [7], Spades [8], Sphinx [9], Sphinxpc [10], Osiris [11], and Synthetica [12]. Unfortunately, none of these are under active development or available anymore. In the commercial domain, SAM [13], MechGen [14], Linkages [15], Ch Mechanism Toolkit [16], MechDesigner [17], and Universal Mechanism [18] have largely focused on simulation of mechanisms. In the recent years, interactive geometry and algebra software tools like Geometer's Sketchpad [19] and Geogebra [20] have become quite popular for simulating geometry of points and lines assembled as mechanisms. Some other currently available freeware kinematic simulation tools are Linkage Mechanism Simulator [21], PMKS+ [22, 23], and GIM [24]. Simionescu [25, 26] has created a library of Pascal subroutines for simulation of different types of mechanisms, which engages students in writing their own computer programs. Similarly, Schmidt and Lax [27] have also implemented computer programs in Matlab and Python for kinematic simulation of mechanisms. While most of these software provide varying level of simulation capabilities, they lack in providing students and industry practitioners design functions to help them create mechanism design concepts.

In higher education institutions, mechanism synthesis is typically a component of junior-level kinematics of machinery and mechanisms courses. However, the learning outcomes of such courses mainly concentrate on kinematic analysis, such as degree-of-freedom calculation, classification, velocity, acceleration, force and torque calculations, which presents a monotonous and



(a) Six-Bar Mechanism (b) Prototype

Figure 2: A Six-bar mechanism (left) and prototype of the device (right) for STS motion shown in the two extreme configurations

passive way to introduce a fascinating subject. Creation of mechanism design concepts is the most crucial step in the machine design process and usually requires creativity and experience. Synthesis represents the highest level of Bloom's taxonomy [28], thus mechanism design exercises are typically postponed to later stages in the course, and are integrated into an end-of-the-semester design project. By this time, it may be too late to cultivate students' interest in synthesis or for instructors to teach it thoroughly. Furthermore, the synthesis component of such courses usually focuses on two- or three-position synthesis problems for motion generation, using a graphical approach. Path synthesis problems, which concern the design of mechanisms that can trace a given path, are addressed using an Atlas-based approach, which involves selecting from a graphical database. A lack of authentic and effective mechanism design tools suitable for classroom teaching has further limited instructors' ability to provide effective design education.

It is of utmost importance for students to acquire the skill of mechanism design, as it is a fundamental requirement for their senior design, robotics, mechatronics, and advanced kinematics classes [29]. Our position is that mechanism design should be introduced early in the curriculum, in order to stimulate and inspire students to create mechanical systems and robots that serve a specific motion objective for real-world problems. Additionally, it is advisable to introduce these concepts as early as the freshman year, which will provide students with an early exposure to the fundamental principles of mechanism design that are embedded in practical scenarios [30]. An example of such an approach is shown in Figure 2, which displays a Sit-to-Stand mobility assist device created by the author and his students to aid individuals with neuro-muscular disabilities. This device is based on a novel six-bar parallel mechanism that mimics the natural kinematics of the human body during sit-to-stand motion. By introducing students to such problems and involving them in design exercises early in their academic careers, they can undergo a transformative learning experience, providing them with a sense of purpose and agency to learn mechanism design.

Therefore, one of the goals of our research has been to create an intuitive and simple mechanism design tool for robots and machines, which can provide both simulation and synthesis capabilities. This paper introduces such a tool called MotionGen Pro [31] available at `http://www.motiongen.io` originally developed in the Computer-Aided Design and Innovation Lab in the department of Mechanical Engineering at Stony Brook University. MotionGen Pro provides

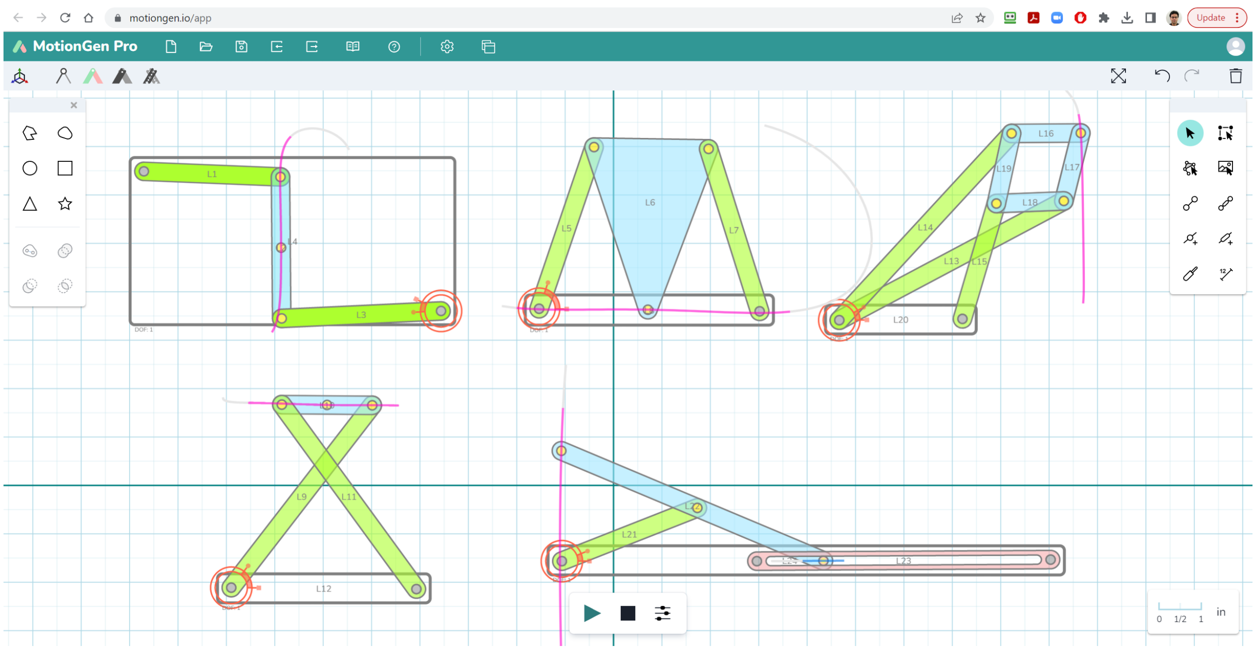


Figure 3: MotionGen Pro interface showing a few straight-line generating mechanisms

simulation of N-bar, one- and multi-degree of freedom planar mechanisms consisting of both revolute and prismatic joints. It also provides path synthesis capabilities for an arbitrary path sketched by users as well as N-position synthesis for motion generation problem. The software is designed to be used with any modern browser to provide cross-platform capabilities and broader access, thereby eliminating the need to download or maintain the software. While the software can simulate linkage mechanisms with an arbitrary complexity of topological structure (serial, parallel, and hybrid mechanisms), it also enables both linear and rotary actuators to be placed on any of the joints. Figure 3 illustrates a few straight line generating mechanisms that have been simulated using this software. The rest of this paper is organized as following. We first discuss the simulation capabilities in Section 2 with a brief discussion of the key algorithm used. Next, in section 3, we present the path synthesis of planar four- and six-bar mechanisms, and finally in section 4, we present an implementation of a motion generation algorithm, which computes both type and dimensions of planar four-bar mechanisms. This software application is a demonstration of a data-driven approach to mechanism synthesis while enabling students to learn mechanism design.

2 N-Bar Planar Mechanism Simulation

MotionGen Pro employs a unified simulation algorithm that circumvents the need for separate loop closure equations for mechanisms with distinct topologies. Specifically, employing a reinterpretation technique, dyads (i.e., pairs of connected links) such as RP, PR, or PP, where R denotes a revolute joint and P a prismatic joint, are approximated as RR dyads. This approximation reduces all geometric constraints of a mechanism to only include revolute joints, thereby eliminating any heterogeneity or incongruity in the constraints and simplifying the simulation. The drawback of this approach is that the position analysis of mechanisms with prismatic joints is an approximation, although the incurred error can be minimized. For all practical intents and purposes, the deviation from the actual path or motion of the links is negligible. The software implements two types of

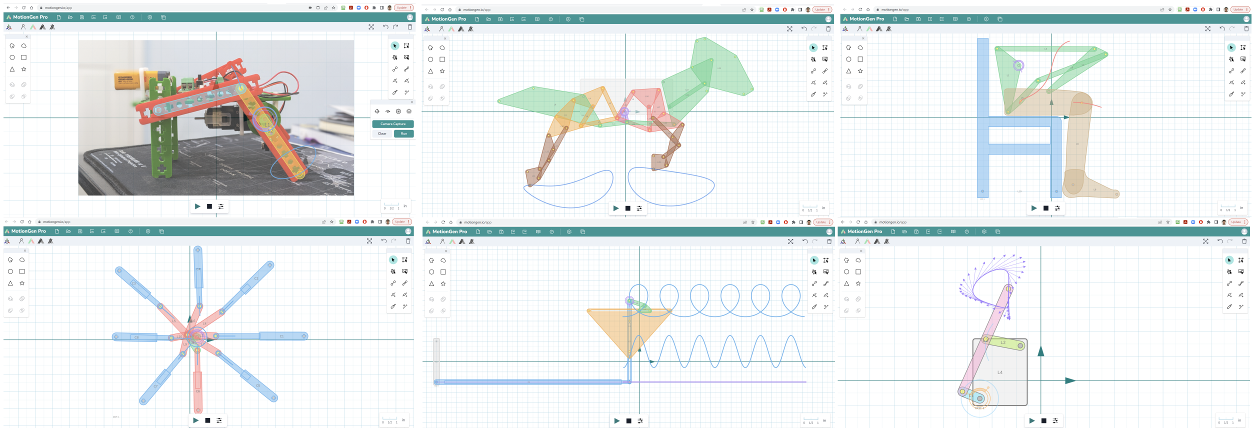


Figure 4: A few editable mechanisms in the public library of MotionGen Pro

solvers: 1) fast dyadic decomposition, and 2) numerical optimization, which can handle even the most intricate mechanisms.

MotionGen Pro also allows users to 1) sketch their own geometries and shapes, which they can attach to individual links of mechanisms, 2) export part geometries for laser-cutting or 3D printing, 3) specify velocity plots for the actuators, 4) observe and export position, velocity, and acceleration data for points of interests and links, 5) record animations and export as video files, and 6) import images over which users can sketch their mechanism. A comprehensive manual is provided in the help menu for users to learn different functions and features of the software. Figure 4 shows a few mechanisms from the public library of MotionGen Pro.

3 Path Synthesis

MotionGen Pro leverages deep learning techniques based on the Variational AutoEncoder (VAE)[32] to offer a multitude of solutions for the path synthesis problem, thereby aiding users in the conceptual design phase[33]. This work builds upon the foundation laid by Deshpande and Purwar [34] in using machine learning (ML) for kinematic synthesis.

The software adopts a Convolutional Neural Network-Variational AutoEncoder (CNN-VAE) model to learn the probability distribution of coupler curves of planar four-bar and six-bar mechanisms and their mapping to the dimensional parameters of mechanisms. By sampling in the latent space of the VAE, it generates up to 30 mechanisms, capable of tracing an input curve drawn interactively on the canvas. Figure 5 illustrates an example where an approximate path taken by the ankle during a walking motion is sketched on the canvas using a mouse. In the event of designing a robot mechanism that can simulate this path, the Path Synthesis option generates 30 mechanisms, six of which are depicted.

4 Motion Synthesis

MotionGen Pro utilizes an algebraic fitting algorithm for the simultaneous type and dimensional synthesis of planar four-bar mechanisms for the motion generation problem, as established in previous research [35, 36, 37]. The software's ability to generate solutions in real-time allows users to efficiently evaluate and modify designs as necessary. The problem is defined by a set of positions of the coupler and, optionally, locations of fixed or moving pivots, which can be inputted by

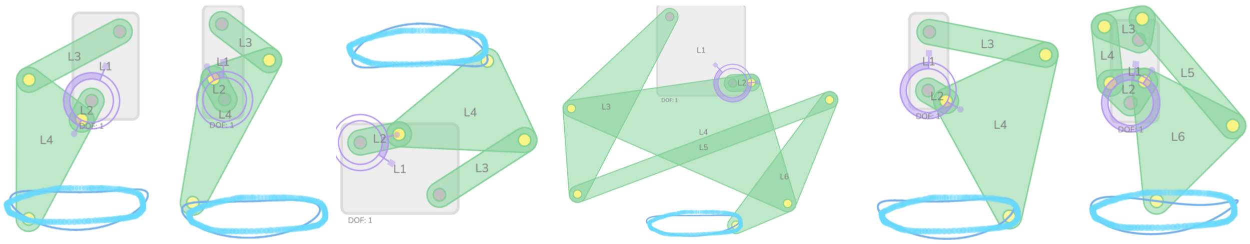


Figure 5: Path Synthesis function in MotionGen Pro generates a series of planar four-bar and six-bar mechanisms for an input curve drawn by the user.

the user. However, given that only up to five positions can be interpolated exactly by a four-bar, solutions for more than five positions are often approximate and impractical. For optimal results, it is recommended that users input five positions, four positions and one constraint, three positions and two constraints, or two positions and three constraints. Multiple constraints on pivots can also be specified to generate a larger set of solutions.

In the unified approach employed by MotionGen Pro, the geometric constraints of all types of dyads of four-bar mechanisms are formulated by a single design equation, together with practical design constraints such as the location of fixed pivots. A singular value decomposition based algorithm is then applied to identify the least squares fit of the given positions, yielding candidate solutions. A quartic polynomial is subsequently utilized to generate up to four real solutions each of which represent a mechanical dyad. By assembling two dyads at a time, the software can provide up to six planar four-bar mechanisms. However, the generated mechanisms are not guaranteed to pass through the input positions in the correct order or same assembly mode, which may require further adjustments to the input positions. Figure 6 presents an illustration of a planar four-bar mechanism passing through five positions without any assembly mode or order defect. Nonetheless, this is often a challenging problem to solve.

5 Classroom Usage

As of April 2023, MotionGen Pro is being used by 6,210 registered users world-wide (no cost) across 145 countries in in colleges and universities, high-schools, which teach the author's Freshman Design Innovation class through Stony Brook University's Accelerated College Education (ACE) program, and in informal STEM learning environments, such as summer and after-school robotics programs. Among several classes at Stony Brook University, it is being used in Freshman Design Innovation class to help students learn practical and exploratory mechanism design. For example, one of the homework assignments requires students to design and physically prototype a mechanism for sweeping action. The mechanism is required to be attached to a mobile robot platform for autonomous sweeping of the floor. Students are first encouraged to determine the motion requirements and consequently create mechanism design concepts. Windshield wiper mechanisms are demonstrated as a good starting point to help scaffold their learning and at least one in-class workshop is organized to help students learn the basics of the software. They are also asked to watch the video tutorial series at https://youtube.com/playlist?list=PLI_dvKowg23EsxpAirEcnaC2nmUiBChLq and consult the manual available in help menu of the software. The author provides an example of one wiper on front windshield found in some Mercedes Benz models; see Fig 7. Students are given the following criteria for a good design: 1) maxi-

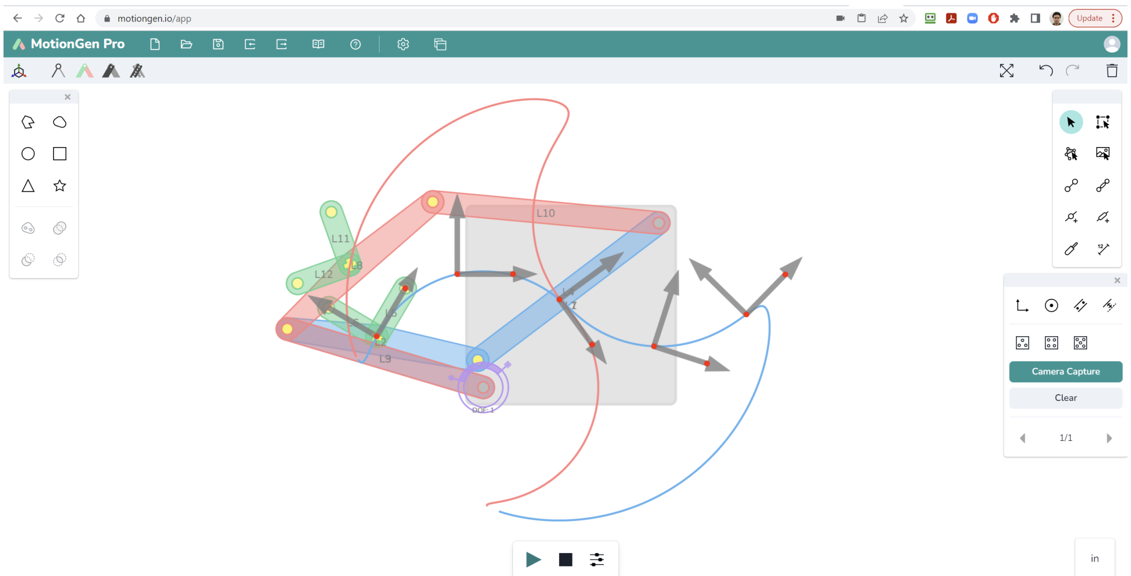


Figure 6: Motion Synthesis function in MotionGen Pro generates planar four-bar mechanism for five positions; both the assembly modes are shown in different color to help students appreciate the circuits and branches of four-bar mechanisms.

mize sweep area, 2) minimize time to sweep, 3) least number of motors, and 4) creativity in the mechanism design. A few students' solution first designed in MotionGen Pro and then physically built using SnappyXO Advanced Robotics kit (`http://www.snappyxo.com`) incorporating an Arduino-based microcontroller board are shown in Fig. 8.

Once students have some experience with the software, they are asked to use it for their final capstone robot design project, which places a heavy emphasis on mechanism design aspect. The Fall 2022 website of the project is available at `https://sites.google.com/stonybrook.edu/mec101fall2022`. Interested readers are welcome to make a copy of the google site and use it for their own classes.

MotionGen Pro is also being used in other classes such as Kinematics of Machinery, Mecha-

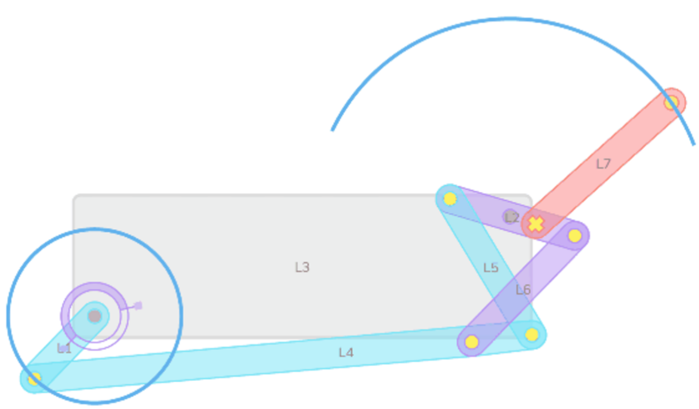


Figure 7: Wiper mechanism in the front windshield found in some Mercedes Benz models

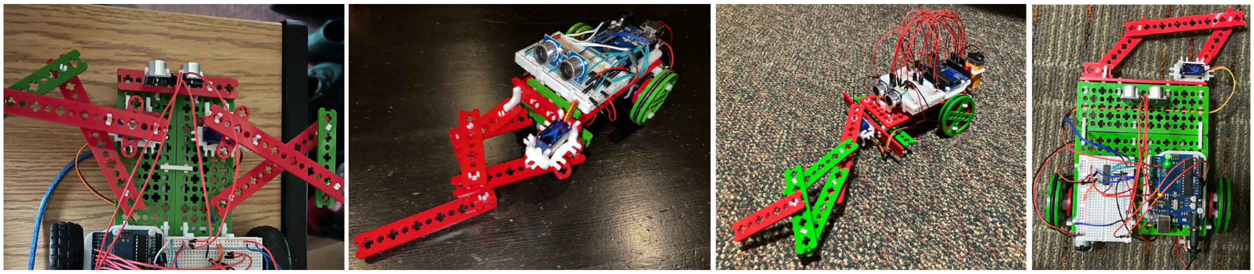


Figure 8: A few students' mechanism design concepts for the sweep motion problem

nism design, Senior Design, Robotics and Mechatronics to help students learn the process of robot motion and mechanism design concepts. Students in these classes typically go beyond using standard hardware and 3D print, water-jet, or laser-cut custom parts exported by the software in the material of their choice.

6 Conclusions

This paper presents a novel software application for robot motion design, utilizing machine learning techniques, that operates within a modern web browser. The application provides a platform for both students and practitioners to learn a fundamental aspect of robot and machine design, specifically the synthesis and simulation of mechanisms. The current version of the software focuses on simulating single and multi-degree-of-freedom N-bar planar mechanisms with both revolute and prismatic joints, path synthesis of four- and six-bar mechanisms, and motion synthesis of planar four-bar mechanisms of all types. The user interface provides a graphical canvas where users can easily sketch the geometry of their mechanism or input path/motion problems. Results are computed in real-time, and the input can be edited to view the outcomes instantly, facilitating a deeper understanding of the interplay between geometry and motion. Although the software is currently being used in various educational institutions, organizations, and high schools, a formal evaluation of its efficacy in achieving learning outcomes is left for future research.

Acknowledgement

This work was supported in part by NSF STTR phase 1 and phase 2 awards #2126882.

Disclosure

The MotionGen Pro software is based on the research conducted in the NSF award (#1563413) to the author as the PI. This product is now being commercialized by a Stony Brook University spin-off Mechanismic Inc. co-founded by the author who also has equity ownership in the Mechanismic Inc. The follow-on research and development of the software has been supported by an NSF I-Corps award (#1823736) and NSF STTR Phase 1 and Phase 2 awards (awards #2126882). The terms of this arrangement have been reviewed and approved by Stony Brook University in accordance with its policy on objectivity in research. All opinions and conclusions presented in this paper are those of authors only and not of funding agencies.

References

[1] Hirose, S., 2020, "IFRR Colloquium on Creative Design", URL http://ifrr.org/creative-design.

[2] Reuleaux, F. and Kennedy, A. B. W., 1876, The Kinematics of Machinery: Outlines of a Theory of Machines, Macmillan, URL https://books.google.com/books?id=WUZVAAAAMAAJ.

[3] Thurston, R. H., 1878, A History of the Growth of the Steam-engine, International scientific series, Kegan Paul, URL https://books.google.com/books?id=G9aCBNsoeTUC.

[4] Erdman, A. and Gustafson, J., 1977, "LINCAGES: Linkage INteractive Computer Analysis and Graphically Enhanced Synthesis Packages,", Technical report.

[5] Erdman, A. G. and Riley, D., 1981, "Computer-aided linkage design using the lincages package", ASME Design Engineering Technical Conferences, 81-DET-121.

[6] Rubel, A. J. and Kaufman, R. E., 1977, "Kinsyn iii: A new human-engineered system for interactive computer-aided design of planar linkages", ASME Journal of Engineering for Industry, **99**, pp. 440–448.

[7] Kihonge, J., Vance, J., and Larochelle, P., 2001, "Spatial mechanism design in virtual reality with networking", ASME 2001 Design Engineering Technical Conferences.

[8] Larochelle, P., 1998, "Spades: Software for Synthesizing Spatial 4C Linkages", CD-ROM Proc. of the ASME DETC'98, paper no.DETC98/Mech- 5889.

[9] Larochelle, P., Dooley, J., Murray, A., and McCarthy, J. M., 1993, "SPHINX: Software for Synthesizing Spherical 4R Mechanisms", Proc. of the 1993 NSF Design and Manufacturing Systems Conference, volume 1, pp. 607–611.

[10] Ruth, D. and McCarthy, J., 1997, "Sphinxpc: An implementation of four position synthesis for planar and spherical 4r linkages", ASME Design Engineering Technical Conferences.

[11] Tse, D. and Larochelle, P., 1999, "Osiris: a new generation spherical and spatial mechanism cad program", Florida Conference on Recent Advancements in Robotics.

[12] Su, H.-J., Collins, C., and McCarthy, J., 2002, "An Extensible Java Applet for Spatial Linkage Synthesis", ASME International Design Engineering Technical Conferences.

[13] Artas Engineering, "SAM (Synthesis and Analysis of Mechanisms)", URL http://www.artas.nl/en.

[14] Associates, M. D., "MechGen", URL http://mechanicaldesign101.com/mechanism-generator-2-0/#MechGen3.

[15] Norton Associates Engineering, "Linkages", URL http://www.designofmachinery.com/Linkage/index.html.

[16] SoftIntegration, "Ch Mechanism Toolkit", URL http://www.softintegration.com/products/toolkit/mechanism/.

[17] Ltd., P. M., "MechDesigner", URL http://www.psmotion.com/.

[18] Laboratory of Computational Mechanics, R., Bryansk State Technical University, "Universal Mechanism", .

[19] KCP Technologies, "The Geometer's Sketchpad", URL http://www.dynamicgeometry.com/.

[20] International GeoGebra Institute, "Geogebra", URL http://www.geogebra.org/cms/.

[21] Rector, D., "Linkage", URL http://blog.rectorsquid.com/linkage-mechanism-designer-and-simulator/.

[22] Campbell, M., "Planar Mechanism Kinematic Simulator", URL http://design.engr.oregonstate.edu/pmksintro.html.

[23] Radhakrishnan, P., Galvan, A., and Brown, D., 2022, "A tool to analyze and synthesize planar mechanisms", URL https://peer.asee.org/41393.

[24] Petuya, V., Macho, E., Altuzarra, O., and Pinto, C., 2011, "Educational Software Tools for the Kinematic Analysis of Mechanisms", Comp. Appl. Eng. Education, **6(4)**, pp. 261–266.

[25] Simionescu, P. A., 2016, "MeKin2D: Suite for Planar Mechanism Kinematics", doi:10.1115/DETC2016-59086, URL https://doi.org/10.1115/DETC2016-59086.

[26] Simionescu, P. A. and Mendoza Diaz, N. V., 2021, "Enhancing Programming Skills to Engineering Students Using MeKin2D Modular Kinematics Subroutines", Https://peer.asee.org/37085.

[27] Peter L. Schmidt, P. E. and Lax, P. A., 2018, "Use of Computer Coding to Teach Design in a Mechanics Course, Resulting in an Implementation of a Kinematic Mechanism Design Tool Using PYTHON", doi:10.18260/1-2--31187, URL https://peer.asee.org/31187.

[28] Armstrong, P., 2010, "Bloom's Taxonomy. Vanderbilt University Center for Teaching", Retrieved 12/24/2021 from https://cft.vanderbilt.edu/guides-sub-pages/blooms-taxonomy.

[29] Macho, E., Urízar, M., Petuya, V., and Hernández, A., 2021, "Improving Skills in Mechanism and Machine Science Using GIM Software", doi:10.3390/app11177850.

[30] Rios, O. and Fadda, D., 2018, "A Conceptual Design Activity for a First-year Mechanical Engineering Course", Proceedings of the 2018 ASEE Gulf-Southwest Section Annual Conference, doi:10.18260/1-2--29666.

[31] Mechanismic Inc., 2022, "MotionGen Pro", URL http://www.motiongen.io.

[32] Kingma, D. P. and Welling, M., 2019, "An introduction to variational autoencoders", Foundations and Trends® in Machine Learning, **12(4)**, pp. 307–392.

[33] Deshpande, S. and Purwar, A., 2020, “An Image-Based Approach to Variational Path Synthesis of Linkages”, ASME Journal of Computing and Information Science in Engineering, **21(2)**, doi:10.1115/1.4048422, URL https://doi.org/10.1115/1.4048422, 021005.

[34] Deshpande, S. and Purwar, A., 2019, “Computational Creativity via Assisted Variational Synthesis of Mechanisms Using Deep Generative Models”, ASME Journal of Mechanical Design, **141(12)**, doi:10.1115/1.4044396, URL https://doi.org/10.1115/1.4044396, 121402.

[35] Ge, Q., Purwar, A., Zhao, P., and Deshpande, S., 2017, “A Task-Driven Approach to Unified Synthesis of Planar Four-Bar Linkages Using Algebraic Fitting of a Pencil of G-Manifolds”, Journal of Computing and Information Science in Engineering, **17(3)**, p. 031011.

[36] Deshpande, S. and Purwar, A., 2017, “A Task-Driven Approach to Optimal Synthesis of Planar Four-Bar Linkages for Extended Burmester Problem”, ASME Journal of Mechanisms and Robotics, **9(6)**, doi:10.1115/1.4037801, URL https://doi.org/10.1115/1.4037801, 061005.

[37] Purwar, A., Deshpande, S., and Ge, Q. J., 2017, “MotionGen: Interactive Design and Editing of Planar Four-Bar Motions via a Unified Framework for Generating Pose- and Geometric-Constraints”, ASME Journal of Mechanisms and Robotics, URL https://doi.org/10.1115/1.4035899, 10.1115/1.4035899.