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Improving Features and User Experience of a Web-based Linkage Analysis Tool through User Studies

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Abstract

PMKS+ (Planar Mechanism Kinematic Simulator Plus) is a web-based tool for the analysis of planar linkages with revolute and grounded prismatic joints. Developed as a classroom and assignment assistance tool with many features and capabilities, PMKS+ is used in different Mechanical Engineering (ME) and Robotics Engineering (RBE) courses at Worcester Polytechnic Institute (WPI).

The goals were to critically assess and enhance the application's user interface so that its built-in features are easily accessible and intuitive for users, thereby expanding the user-base of PMKS+. Comprehensive studies involving the application's primary users were conducted and journey maps developed to discover key pain points. To address these concerns, a complete redesign of the application was undertaken, with a primary focus on improving the user experience for the existing feature set in PMKS+. The user interface was modernized by following modern design guidelines. General conventions were extracted from other engineering applications used by our users to allow an easier transition to PMKS+. High-fidelity interface designs were generated and rigorously reviewed by all stakeholders at various stages of the development process. In conjunction with front-end improvements, significant backend modifications were implemented to decouple analyses modules from user-interface components.

Working prototypes of the redesigned application were evaluated by different groups of students at various stages. The results revealed a significant improvement in user experience with a high satisfaction score.

Keywords: Linkage Analysis; Planar Mechanisms; Four-bar Linkage; User Interface; User Studies

1. Introduction

In the rapidly advancing world of technology, it is crucial for an application to be not only functional but also user-friendly. By adhering to user-centered design principles, applications can be refined to provide a more positive experience for users, addressing their needs and challenges. PMKS+ exemplifies such an application, having undergone significant enhancements in usability in recent years. PMKS+ is a 2D linkage analysis tool designed to assist students in understanding the construction and modeling of planar linkages. It has become increasingly important and relevant in teaching various courses dealing with planar linkages at WPI. In addition to modeling and simulating linkages for detailed analysis, PMKS+ has always maintained a focus on education. The tool encourages collaboration among students working on a linkage, and it supports teaching staff by enabling students to check their work independently. This allows staff to concentrate on the crucial task of teaching students the underlying concepts of linkage design and analysis.

The primary objectives of this project were to assess and enhance the usability of PMKS+. This involved identifying and addressing the challenges and user needs associated with the application.

A redesigned interface, informed by user research and feedback, was implemented, alongside the addition of new features to improve the overall user experience. The effectiveness of these changes was analyzed to determine their impact. Such changes will not only improve the usability of PMKS+ software at WPI but also at other universities with Mechanical Engineering degrees where planar linkages are an important topic in the curriculum.

The paper is organized as follows: Section 2 delves into the background of the application, including its development history and earlier improvements. Section 3 presents user studies and research that guided the redesign process. Section 4 discusses the redesign process in detail, outlining the rationale behind the interface changes and new features. Section 5 showcases the final application, highlighting the key improvements and their impact on the user experience. Section 6 explores potential future work to further enhance the application, while Section 7 concludes the paper with a summary of the findings and their implications.

2. Development History

The PMKS+ software was first developed as a Microsoft Silverlight application for the simulation and analysis of planar mechanisms [1]. It served as the foundation for the development of PMKS+, which aimed to recreate the application on a modern web platform with enhanced user experience and a greater focus on classroom use. Since the start of PMKS+, multiple teams of students and faculty at WPI have contributed to its development by refining features, enhancing the user experience for creating and editing linkages, and adding powerful analysis capabilities. Several reports have been published documenting the migration of platforms as well as the various enhancements and user interface design principles employed throughout the development process [2] and [3]. The development of PMKS+ is guided by several core ideals and principles, which help ensure that the application remains a valuable tool for students and educators in the Mechanical and Robotics Engineering fields.

- Educational: The primary purpose of PMKS+ is to facilitate learning and the intuitive understanding of planar mechanism concepts. The software should be simple to use, allowing students to focus on learning concepts and verifying their work. Unlike other professional tools (such as SolidWorks and Working Model), PMKS+ emphasizes not just the results but also the steps students can take to achieve those results.
- Flexible: PMKS+ should be capable of solving a wide range of problems, not just specific assignments, or linkage types. The application is designed to support several types of planar mechanisms and provide diverse analysis tools, enabling students to tackle complex problems and explore different design scenarios. This flexibility makes PMKS+ a versatile tool, suitable for use in capstone or final projects, not just at WPI but also at other universities.
- Collaborative: The application should facilitate sharing and collaboration, enabling groups to work together on a single linkage. PMKS+ allows users to save, export, and share their designs with others, promoting the exchange of ideas and fostering a collaborative learning environment. This feature is particularly valuable in educational settings, where students

often work in groups and benefit from discussing their designs with their peers and instructors.

- Accessible: PMKS+ should be compatible with multiple operating systems, require no downloads, and be free and open source. The application is developed as a web-based tool, ensuring that it is accessible from various devices and platforms without the need for installation. Additionally, PMKS+ is available at no cost, making it an accessible resource for students everywhere.

2.1 Flaws in the Existing Version and Motivation for Redesign

The version that students used before the redesign proposed by the authors is shown in Figure 1 and consists of four main components: *Toolbar*, *Grid*, *Linkage Table*, and *Animation Bar*. The *Grid* is used to create the *Mechanism*, the *Animation Bar* sets the animation and displays helpful information, the *Linkage Table* shows properties of joints, links, and forces, and the *Toolbar* offers access to resources and settings within PMKS+ [3]. The software can be used to create mechanisms with revolute and grounded prismatic joints. The designs created within the software can be shared through the built-in URL generation feature.

One key issue identified in the version shown in Figure 1 was the difficulty in accurately recreating the linkage users wanted to analyze. If the linkage is specified in the form of joint coordinates, then it could be easily created within PMKS+ but not when the linkage is specified in terms of link lengths and angles. This creates an impediment to the adoption of PMKS+ at other universities since many textbooks in this domain have sample problems specified in terms of link lengths and angles. Users also had trouble locating features such as plots and equations that could be used to verify or troubleshoot errors in different assignments. Besides, the existing library of link shapes had limited adjustability.

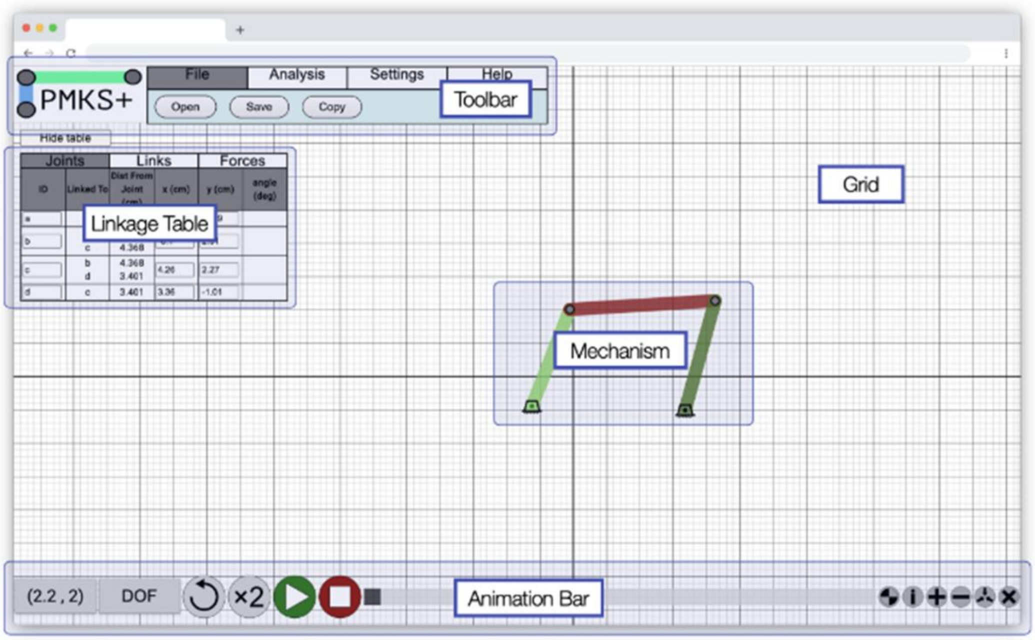

Figure 1 The original application has four main sections: The *Grid*, *Toolbar, Linkage Table*, and *Animation Bar*.

3. User Studies and Research Guiding Redesign Process

Gaining a thorough understanding of the users and the context of the application is crucial for conducting a redesign with maximum benefit. There were three user studies performed during this redesign process and the first one was used to get a better idea of the current state of the application before the redesign started. In the fall of 2022, fifteen students, who had used PMKS+ for a full term while working on various projects were interviewed about their experiences. Through this process, two distinct user types were identified, each with a unique set of challenges. Based on aggregated data from past work ([1], [2] and [3]), we were able to get a better idea of the current user base of the application. Here were some key insights:

- Close to 100% of users were students at WPI. Since PMKS+ has only been promoted through word of mouth, only users who are affiliated with this university use the software.
- Most users are either Mechanical or Robotics Engineering majors.
- Most users are familiar with SolidWorks CAD tool.

Based on these comprehensive surveys, along with multiple unstructured interviews with other stakeholders, two user personas were developed to represent the primary user groups:

- Persona 1: A student who is required to use PMKS+ as part of their coursework. These students use the tool to validate their MATLAB results by recreating and analyzing mechanisms provided in assignments. They have a clear idea of what this linkage looks like since it is provided to them in the assignment, although different problems present the linkage in various formats.
- Persona 2: An engineering student working on Major Qualifying Projects (MQPs) or other final projects who wants to design a linkage. For these users, PMKS+ is a useful tool for saving time on rough calculations and validation.

Most users currently fall into the Persona 1 category since the primary method of discovery for this application is through its required use in certain classes. For both personas, the biggest barrier to getting the desired data from the application was the time it took to create a linkage model that accurately represented their design on paper or from their thoughts. Although the users of the application are the primary stakeholders of PMKS+, there are two other groups that should be considered: Professors teaching courses where PMKS+ is used for assignments, along with their teaching staff.

3.1 Pain Points

By getting a comprehensive understanding of our users, several key pain points in PMKS+ were identified as listed below:

- Lack of discoverability and access to analysis features: Users currently need to switch tabs, open a popup, and select from two dropdown menus to access analysis features. An example is given in Figure 2 that shows the steps required to obtain the plot of the velocity at the center of mass of link BC in a four-bar linkage, which involves a total of seven steps.

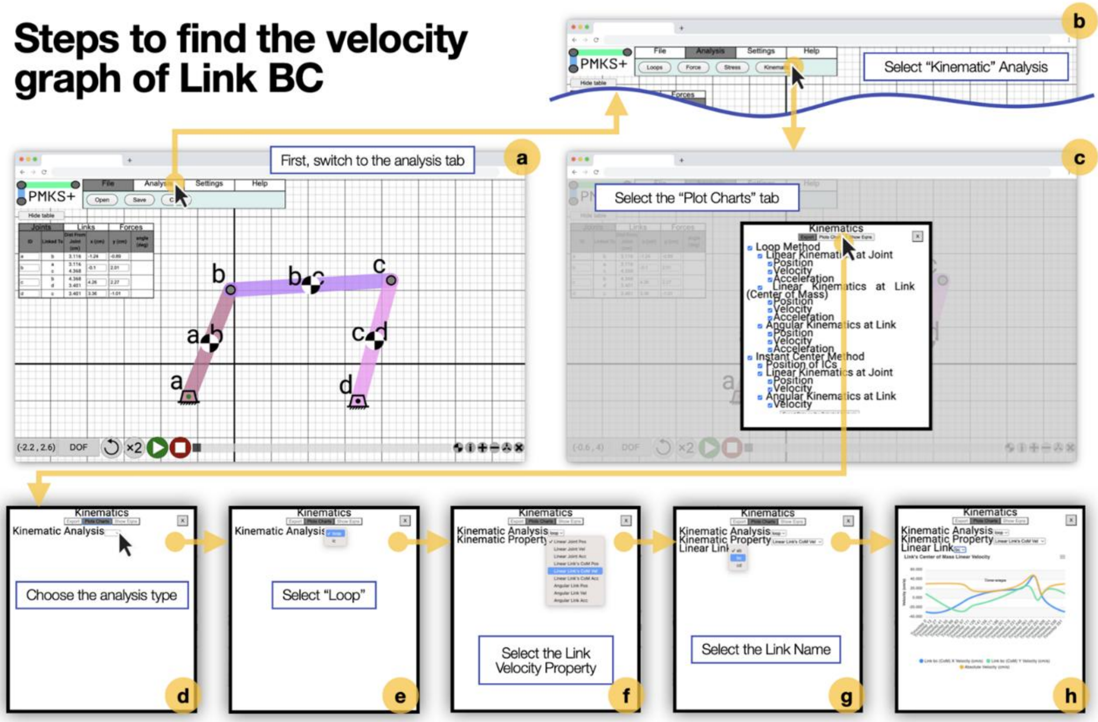

Figure 2 Series of images showing the process to obtain the plot of velocity of the center of mass of link BC.

- Linkage table issues: Users reported issues with the limited number of digits displayed in the table. This is important because a typical user spends the largest amount of their time creating the initial linkage design.
- Link Shape: Students struggled to create the exact shape of the link they wanted. Users must switch to a different mode, enter edit shape mode, and click save when finished. Selection is limited to a list of predetermined shapes, and users must scale, move, and rotate the shape to fit over the joints.
- Limited grid and workspace range: The grid has a limited usable area, meaning users cannot make linkages that are too small or too large. This forces users to perform additional unit conversions to ensure their entire linkage fits within this area.
- Various quality of life issues and bugs: Small bugs and issues can have a significant impact on user experience. For instance, labels for links and forces cannot be renamed, making it challenging to keep link names consistent with assignments.

3.2 Competitive Analysis of Existing Linkage Analysis Software

The following factors were considered essential for users when selecting a linkage analysis application: User Interface and Ease of Use; Licensing and Accessibility; Kinematic Analysis; Force Analysis; Linkage Synthesis and Educational Focus. Based on the criteria, Table 1 summarizes the capabilities of software tools that were reviewed for competitive analysis. Those included Working Model [4], Linkages [5], SAM [6], SolidWorks [7], and MotionGen Pro [8]. Currently, there is no free and easy-to-use software that is education-focused while providing powerful kinematic and force analysis capabilities. A more thorough overview of each software has been conducted in our previous work [3]. This reveals a significant opportunity for the development of a new software tool that addresses these limitations and offers a comprehensive solution for mechanism design and analysis. The PMKS+ software presents a unique opportunity to fill this gap by incorporating the desired features and remedying the shortcomings of existing tools. This will allow utilization of the PMKS+ software at other universities as well.

Table 1 key features in currently available linkage analysis

Features / Software	Working Model	Norton Linkages	SAM	Solidworks	MotionGen Pro
Kinematic Analysis	✓	✓	✓	✓	✓
Force Analysis		✓	✓		
Synthesis Options			✓		✓
Quick to Create Mechanism			✓		✓
Quick to Analyze Mechanism		✓	✓		✓
No Installation Required					✓
Free To Use					✓
Display Analysis Equations for Checking Work					
Source code available					

4. Redesign Process

Initial sketches and basic wireframes were created to explore potential user interface (UI) elements that addressed the primary redesign goals. These ideas were informed by a deep understanding of user needs and preferences. The first high-fidelity mockup reimagined the interface for entering and editing joint and link properties. In addition, prototypes for viewing analysis data were also created and one such is shown in Figure 3. The linkage table in the current version of PMKS+ (shown in Figure 4) displayed extraneous information that often-lacked immediate relevance to users.

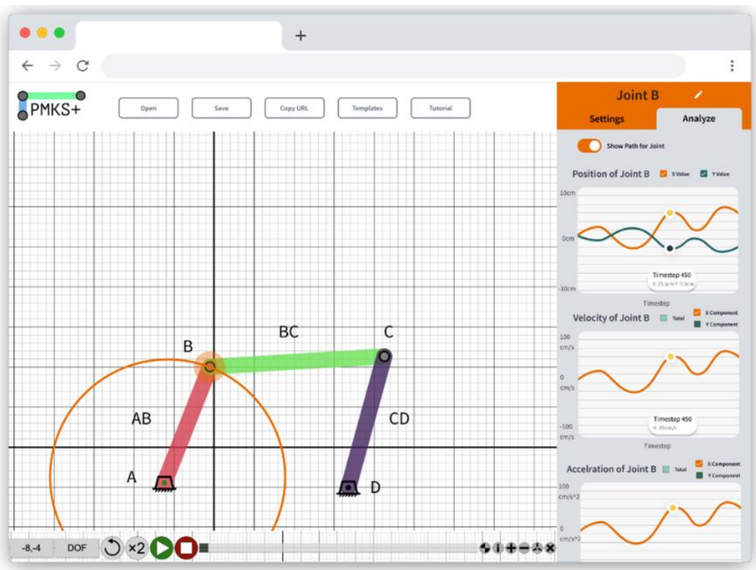

Figure 3 Mockup one introduces the idea of clicking an object to select it. The right panel displays details for the selected object.

Replacing this with a progressive disclosure approach, the mockup introduced the concept of an active or selected object, displaying only its information on the screen. This change offered several benefits, including increased screen real estate for linkages, enhanced legibility of text and input boxes, and the ability to display and edit more object properties. Furthermore, the availability of analysis options in the same area as editing options significantly improved their discoverability, a key advantage of this mockup. However, the design also presented some drawbacks, such as the right panel occupying a constant amount of space, reducing the overall visible grid area.

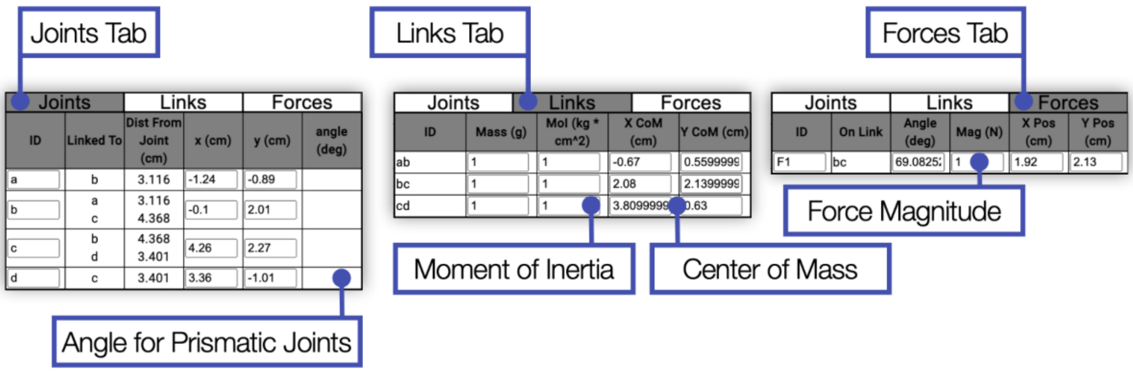

Figure 4 The various tables that allow users to enter information within the older version of PMKS+ Software.

The second mockup (Figure 5) was developed to emphasize the linear progression of synthesizing, editing, and analyzing a linkage. Users typically synthesize a linkage when starting with a blank file and can only simulate and analyze the linkage after assembly. This prototype successfully addressed the main design goal of feature discoverability and guided users through the expected sequence of events. However, the unidirectional popup approach presented a significant drawback: it discourages prototyping within the app.

The user flow diagram in Figure 6 illustrates numerous reasons for users transitioning between the three modes. Constraining users to a strictly forward progression renders each step more final and challenging to undo. This limitation is particularly detrimental to persona 2 type users, as it obscures the possibility of alternating between editing and analysis to fine-tune linkages.

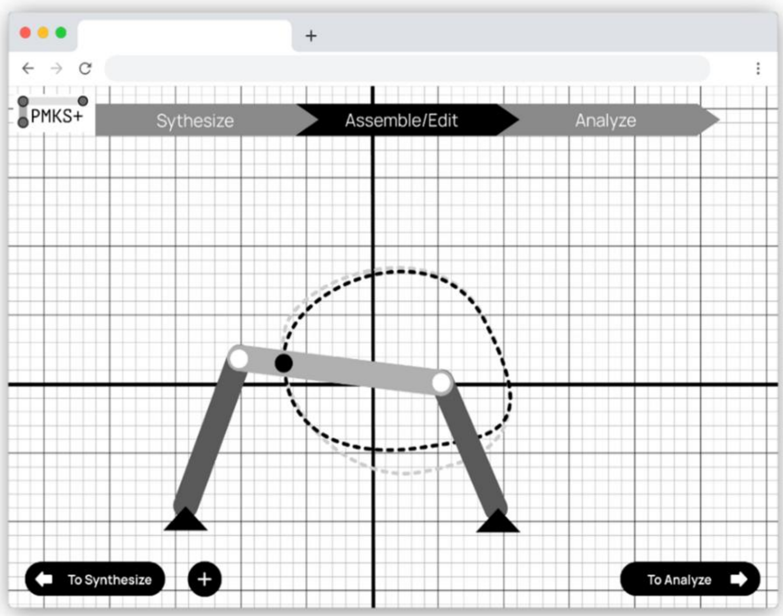

Figure 5 Mockup 2 leans into the idea of the three modes (Synthesis, Edit, Analyze) being a linear process that a user goes through.

Previous versions also suffered from inconsistency in design elements, such as button sizes, colors, border radii, and text styles. To facilitate a more accessible and intuitive user experience, a design framework was adopted. Given that the target users frequently interact with Google services, the Material Design guidelines [9] were selected to provide a cohesive framework for constructing visually appealing and functional interfaces. This approach aimed to minimize the learning curve by enabling users to rely on pre-existing knowledge of UI conventions.

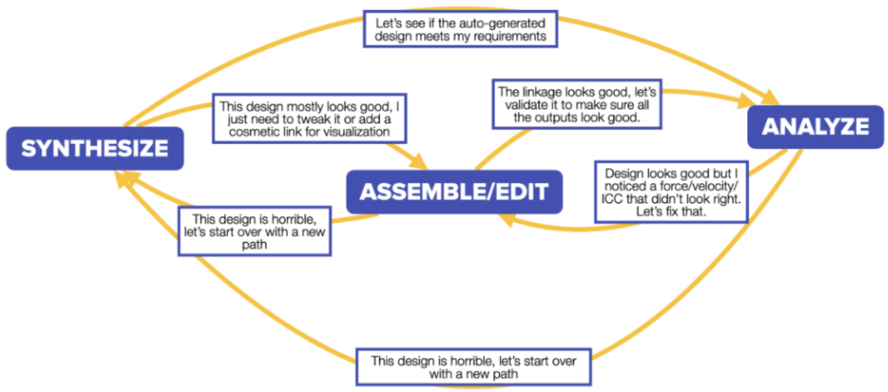

Figure 6 A flow diagram of PMKS+ software with modes in the solid blue boxes: Synthesis, Edit, and Analyze.

4.1 Toolbar and File Options

Compared to the original PMKS+, many actions such as creating a new mechanism or saving one have been relocated to the settings panel and analysis panel, streamlining the number of toolbar actions. The first design started by examining other applications users are familiar with. Traditional desktop applications, which utilize a standard File - Edit - View top bar structure, were considered in the redesign. Since all required actions fit within the file category, only the File button was added. In a simulated browser, however, the top toolbar appeared too large and occupied excessive grid space. Furthermore, the additional click needed to reveal the list of options seemed unnecessary given the available space and the small number of options. As it was challenging to create clear, descriptive icons for each action, the final mockup (shown in Figure 7) utilized buttons with both icons and labels. This design ensured a more intuitive user experience by allowing users to quickly identify the function of each button while maintaining a sleek and organized interface.

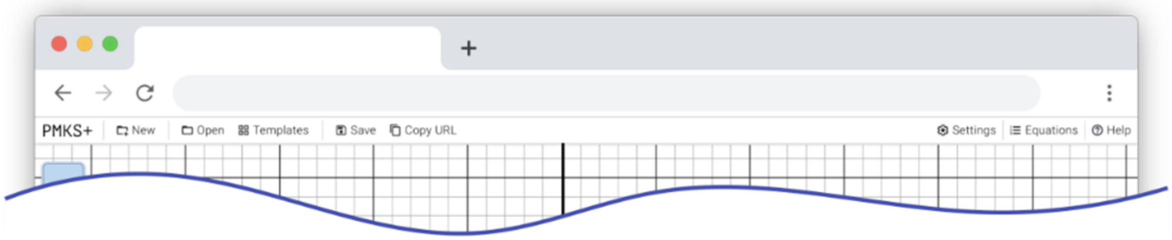

Figure 7 Finalized mockup for the toolbar.

4.2 Tab Designs

The subsequent challenge was determining how users should switch between the three primary modes of the application: *Synthesize*, *Edit*, and *Analyze*. The initial design featured three horizontal tabs, with the selected tab being highlighted. This design met the two requirements of having a hidable panel that allows switching between the three modes, but it had several drawbacks. First, the button to expand and hide the panel was small and not visible enough for a panel containing all the app's features. Second, because the tabs were spelled horizontally, they were too small, and users might not notice the different modes or their current mode. To address these issues, a vertical tab was added on the left-hand side of the screen as shown in (Figure 8):

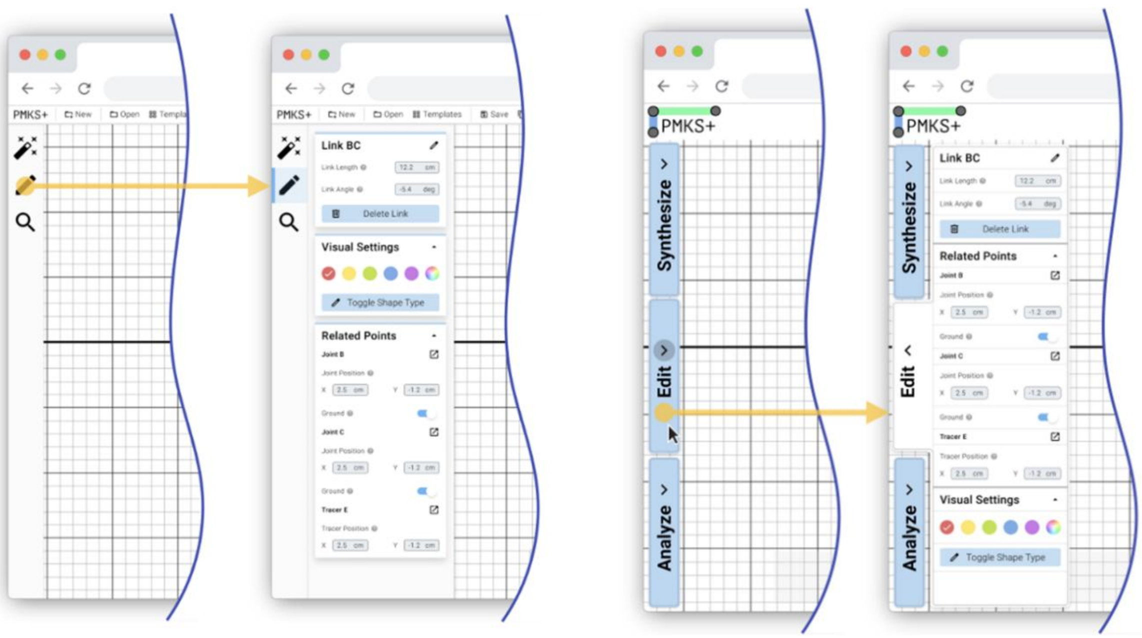

Figure 8 (left) The left panel design converts the three modes into large icons. (right) Instead of icons, the left panel shows text for the three modes. In both mockups, the three modes open into tabs that take up the entire vertical space on the left.

The three primary panels—Synthesize, Edit, and Analyze—are represented by icons, with tooltips displaying labels upon hovering. When users click on any of these icons, the corresponding panel expands, and the button is highlighted, indicating an open panel. Clicking on the currently open panel's button hides the panel again. The primary issue with this version was that the buttons could be confusing, as there is no ideal icon to describe synthesizing a linkage or creating analysis graphs. Additionally, the buttons were not prominent or enticing enough for such a core feature of the app. Finally, there was a considerable amount of wasted white space on the left toolbar, taking up grid space without serving a purpose. The final version pictured in Figure 8 (right) resolved all these issues.

4.3 Edit Panel Design

To develop the interface of the panels, a set of standard input components was needed for use throughout the app. Based on Google's material design guidelines, a collection of components with multiple variants for each was designed. These components can be combined to create any UI element. These blocks were designed to have a consistent aesthetic, ensuring that UIs feel cohesive while being completely modular, allowing blocks to be arranged in any order while maintaining a visually pleasing appearance.

4.4 Infinitely Customizable Shapes

A major pain point to address for this redesign (discussed in Section 3) was the lack of shape customization and options as well as the difficulty of defining joint positions by link lengths. To determine the types of shapes required by users, sample problems from different textbooks and homework problems assigned to previous ME and RBE department classes were analyzed. The shapes used were then categorized into various general categories and ranked by their frequency of use namely binary links, polygons, circles, letter shapes, gears, and cams. Based on discussions with stakeholders and the context of other related projects, the focus was directed toward developing a custom shapes system that could handle the first four types of shapes (not gears and cams). Shown in Figure 9 is an example where users can create shapes by adding additional links to existing ones. By default, links are in convex hull mode, so when a user creates a third link connected to the red binary link and drags it up, the red link becomes a triangle.

The most significant limitation of this approach is the restricted range of shapes that can be created. Given that each configuration of joints only has two shapes, shapes like L or V cannot be created, along with many other simple-to-describe concave shapes. Consequently, a final alternative was devised to reduce complexity while still increasing the possible number of shapes that can be extracted as shown in Figure 10. By *welding* and *un-welding* simple links at the joints, users can combine basic shapes to create any shape that is a combination of the two. This solution addressed many of the previously mentioned issues: It does not require the user to enter a different mode but instead allows them to use the familiar context menu to Weld Joints. Recomputing the shape when a joint is dragged is easier since it is a simple union of shapes. Additionally, this approach does not necessitate tracking the primary axis. This final solution was selected to enable users to customize shapes.

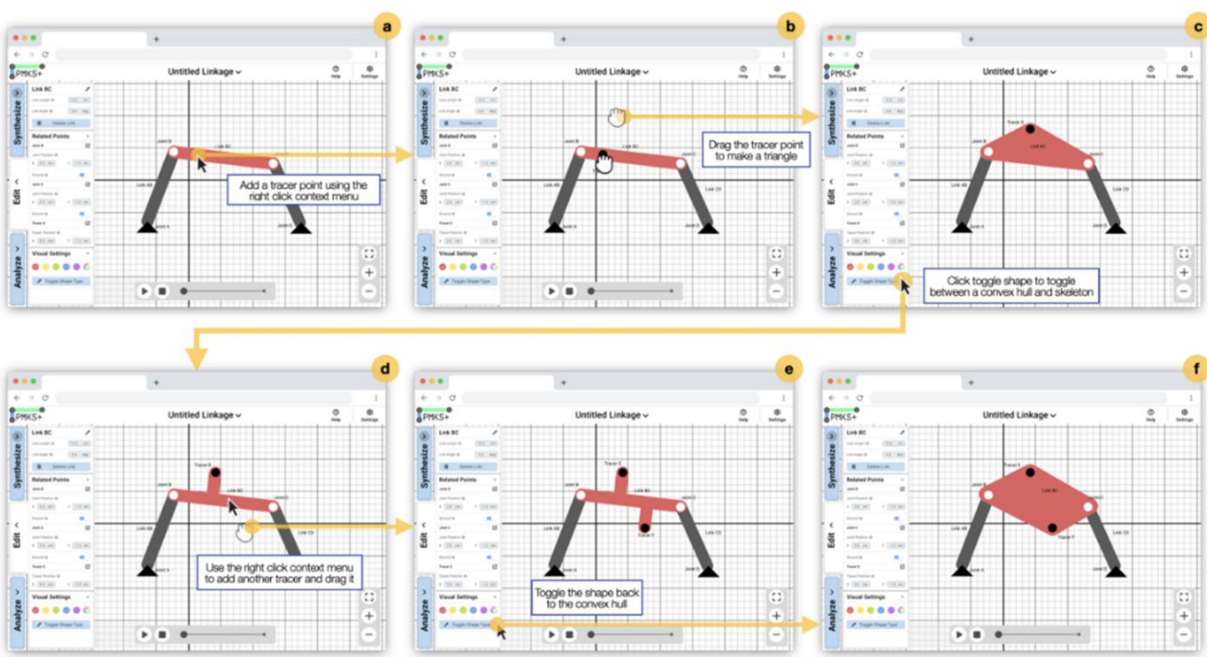

Figure 9 One method of changing shapes of links

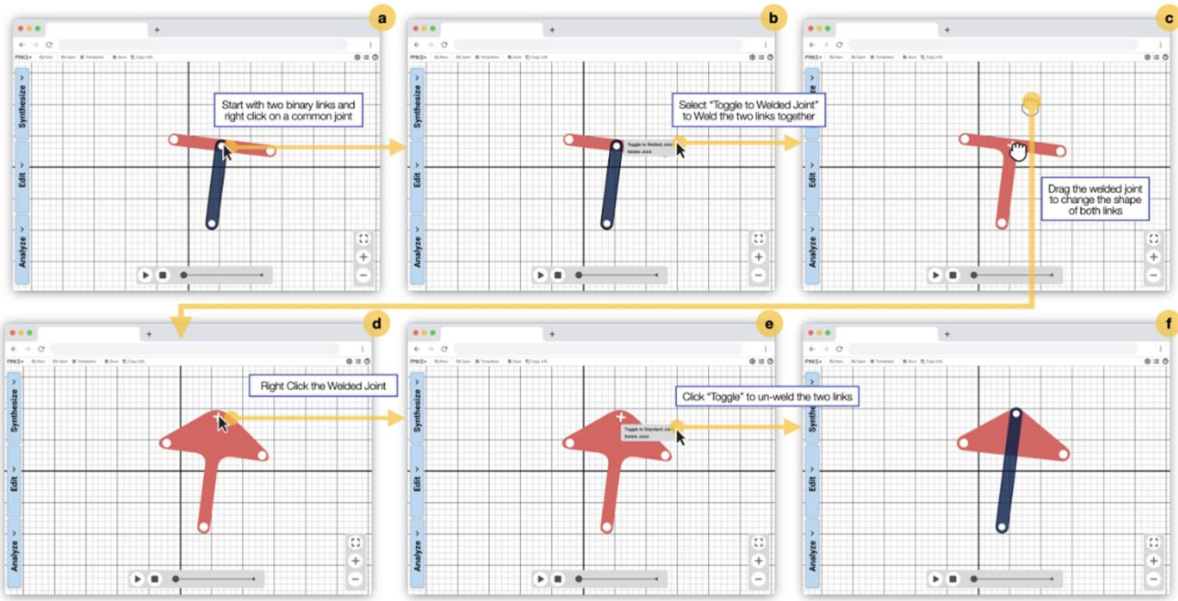

Figure 10 Finalized link shape system

4.5 Early Feedback from Users

As mentioned in previous sections, obtaining constant feedback from users was emphasized during this redesign. As soon as the mockup version of the redesign was completed, feedback was sought. The participants included sixteen students, who had experience with the PMKS+ software. Overall, users showed a strong preference for the new editing options, scoring it 4.875/6. Similarly, all participants preferred the new analysis options, giving it a score of 4.375/6. For synthesis, students gave a 5/6. Note that a neutral score (indicating no preference between the PMKS+ and the mockup) would be 3/6. The results are shown in Figure 11. More importantly than the positive feedback, numerous quotes and images were collected from this study, providing valuable insights into the users' experiences with the mockup.

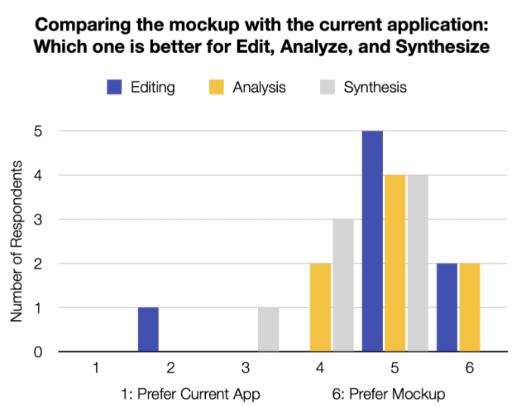

Figure 11 A study in October 2022 asking 16 participants to compare the current app with the mockup shows an overwhelming preference for the mockup.

Encouraged by the positive feedback, a basic prototype was developed. The primary goal was to validate the concept of selecting an object, which was the fundamental change in this redesign. To do this, feedback was sought as soon as the prototype was completed. The old PMKS+ interface was compared with the redesigns. This user test was conducted from December 11, 2022, to December 19, 2022. The results of this user test indicated a slight preference towards the new editing process, with a score of 2.96/5, where a no-preference score would be 2.5. While analysis and synthesis were not implemented in the prototype, feedback echoing the results from the previous study was still received, with a score of 3.87/5 and 3.2/5, respectively. Interestingly, the score for editing significantly decreased compared to when the mockup was presented. It is believed that the rating was impacted due to the number of bugs in the program rather than the actual interactions. Despite the number of bugs, the fact that students preferred the prototype over the current application was a positive sign. The results are shown in Figure 12.

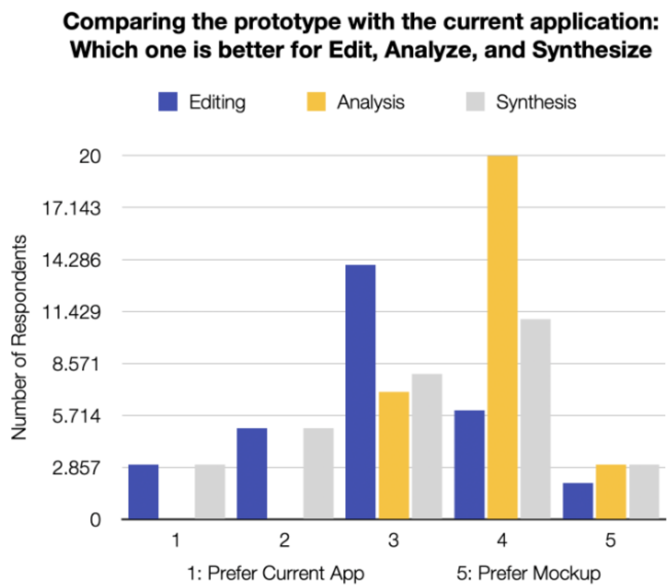

Figure 12 Summary of prototype testing by students

5. Finalized Application

The redesigned application, shown in Figure 13, maintained a familiar interface, featuring a grid that occupies the entire screen, accompanied by a toolbar at the top and an animation bar at the bottom. The toolbar provided quick access to common tasks, while the animation bar allowed users to control the simulation of the linkage animation and their view of the mechanism. In contrast to the original linkage table, the updated version incorporated three tabs on the left and three buttons on the right that open corresponding panels. Only one tab could be open at a time for each group (left and right). The left tabs can be closed, or opened to edit, analyze, or synthesize. The synthesis tab enabled users to generate a linkage based on the desired positions of one of the links automatically. When the edit tab was open, users could modify the properties of the selected object (highlighted on the screen in amber color). The analysis panel, when open as shown in Figure 14, allows users to view kinematics and force analysis graphs for the selected object. The right tab group can be closed or opened to display settings, the help panel, or the equations panel. The settings panel (open in Figure 14) enabled users to modify overall mechanism settings, such as units, input speed, and enabling gravity, as well as visual settings such as mechanism size and grid line visibility. The animation bar had similar features to the previous version.

To further enhance user engagement and understanding, a direct feedback mechanism has been introduced, enabling users to submit support requests and feedback through the help tab. Users can optionally add their email to receive a reply and send diagnostic data gathered from their device. This approach allows the development team to stay connected with user needs and address any issues users may encounter, improving the overall user experience.

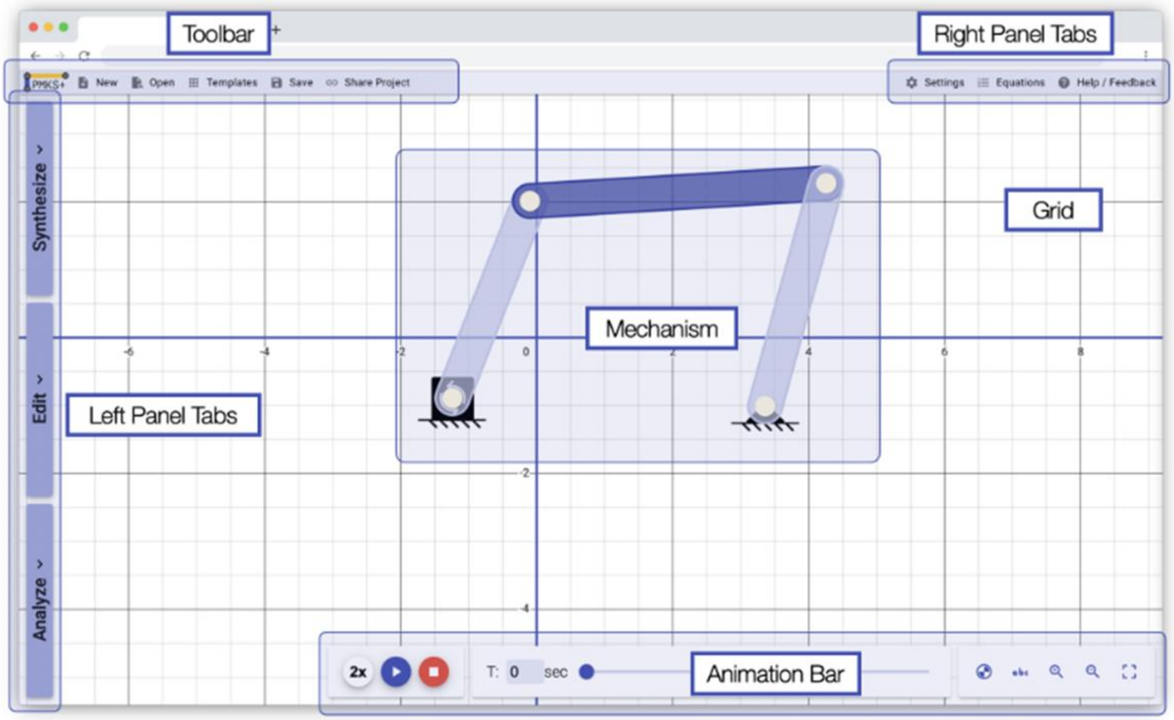

Figure 13 The redesigned application has a familiar interface with the grid as the background.

5.2 User Testing

The final test was conducted on April 11th, 2023, with a 5-user focus group in person. The test began with a 5-minute demographic survey, followed by a 5-minute task description without showing the participants PMKS+. The participants then spent 20 minutes performing the task, during which time each researcher asked three people to do a cognitive walkthrough with a think-aloud protocol. The session concluded with a 20-minute open discussion, during which the researchers asked the whole group open-ended questions. One of the key hypotheses for this validation test was that the new design would increase the organic discovery of analysis features. Although none of the users had previously used this redesigned version of PMKS+ and most of them did not have any experience with any version of PMKS+, all five participants discovered and utilized the following features during their 20-minute test of the app: opening the right-click context menu to edit the mechanism, editing joint properties with the edit panel, editing link properties with the edit panel, editing force properties with the edit panel, analyzing joints and links with the analysis panel, and using the animation bar for playing the animation.

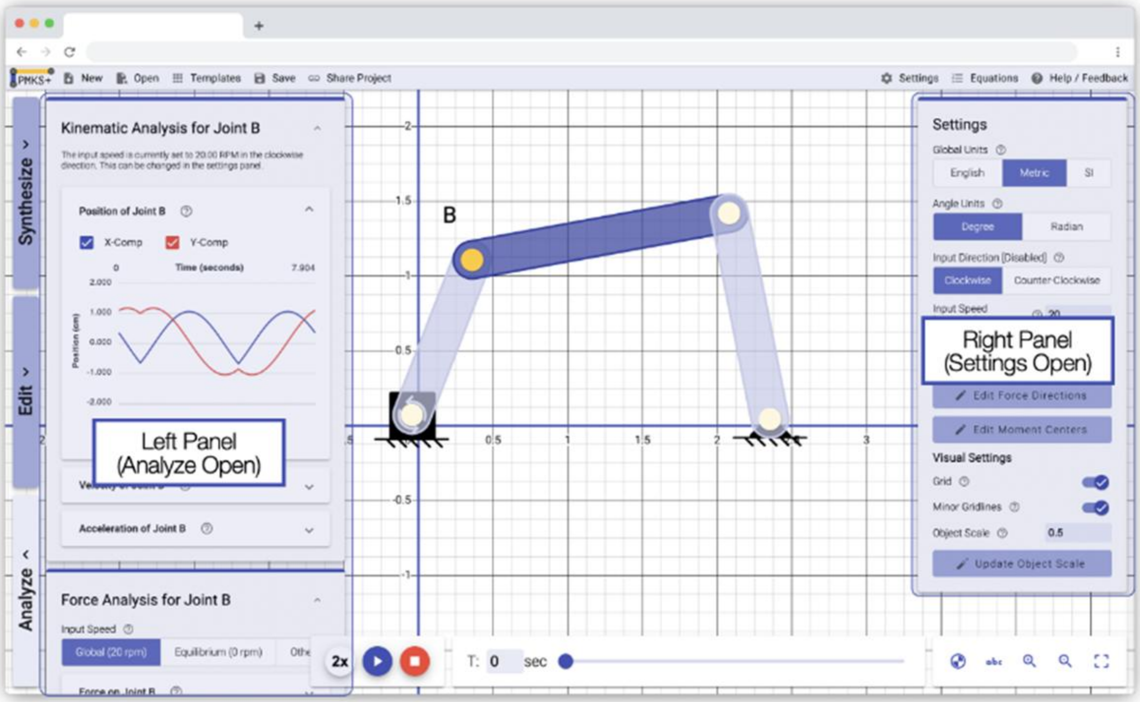

Figure 14 The three tabs on the left opens the left panel and the buttons on the right of the toolbar open the right panel.

6. Discussion and Future Activities

The paper showcases a comprehensive approach to designing and redesigning software for use by mechanical and robotics engineering students and educators. User studies and demographic research have provided essential insights into the needs and preferences of our target audience. By actively engaging with our users through heuristic evaluations, focus group discussions, and validation testing, we have been able to identify and prioritize features that have the most significant impact on our users. One of the primary successes of our development process is the increased organic discovery of analysis features. User testing has shown that even without prior experience or tutorials, users can discover and utilize essential features of the application. This outcome is a testament to the effectiveness of our redesigned user interface and its ability to promote user engagement and learning. Informed by user studies, we created high-fidelity mockups, which have allowed us to rapidly visualize and iterate on the UI based on user experience. These mockups have guided the design process and enabled us to address key usability concerns. Accessibility has been a cornerstone of our development philosophy, with our commitment being further reinforced by our user studies and mockup iterations. By testing our application through colorblind filters, screen readers, and various devices and browsers, we have ensured that PMKS+ remains an accessible and intuitive platform for users with diverse abilities and backgrounds, while keeping it a free and open-source program for anyone to utilize and learn from. Though the application highlighted is for planar mechanism design and analysis, the methods showcased here are applicable for other applications in this domain.

Based on the user studies conducted by our team, and those from previous years, we have compiled a list of features that will be implemented in the future. These are ranked in order, considering the amount of work each task requires and the overall benefit to the user in this prioritization. These include:

- Updating *Save* and *Open* features to accommodate all new features and avoiding user frustration and loss of work.
- Integrating stress analyses, which requires users specifying cross-sectional areas of links and joints. This will help users understand the structural performance of their designs.
- Redesigning the *Templates* menu to provide a more visually appealing and intuitive menu, thereby allowing users to quickly select a linkage for their design needs.
- Integrating Undo/Redo will allow users to experiment more freely and confidently without fearing loss of data.
- Displaying the equations and loops, which was in an earlier version, will be redesigned and implemented.
- Integrating additional synthesis techniques such as path synthesis and function synthesis for linkages, including support for multiple mechanisms, to allow generating designs for animatronic applications.

Once these features are integrated, PMKS+ will evolve into a comprehensive and accessible tool for designing and analyzing planar linkages.

Currently, the user base for PMKS+ is at WPI. While there has been success in reaching out to professors who teach linkage analysis courses and getting them to utilize the software, further efforts are needed to expand the user base beyond the home university. This can be achieved by actively advertising the project online, at conferences, and at other educational institutions. Creating a better landing page highlighting all PMKS+ features and implementing improved search engine optimization will also help attract more users.

7. Conclusion

The development of PMKS+ has been an ongoing collaborative effort, with each team contributing to the project and building upon the work of their predecessors. Reimagining the user experience to ensure that users can discover advanced analysis features is shaping PMKS+ into an invaluable tool for ME and RBE students and educators at WPI and beyond. Informed by user studies, we created high-fidelity mockups, which have allowed us to rapidly visualize and iterate on the UI and user experience. These mockups have guided the design process and enabled us to address key usability concerns. The potential of PMKS+ to revolutionize the education of mechanical linkage design and analysis is immense. By continuing to actively solicit and incorporate user feedback, we will ensure that our application evolves in response to the ever-changing needs of students and educators.

References

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