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INTEGRATED PROJECT-BASED LEARNING: DESIGNING AND TESTING A SMALL-SCALE MOBILE WORK PLATFORM LIFT

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Abstract: This paper presents an integrated project-based learning (PBL) approach to designing and testing a small-scale mobile work platform lift. The project was assigned to the Mechanical Engineering students as the final work in the Integrated Project subject, which required the application of various concepts and theories from prerequisite subjects. The objective of the project was to design, simulate, produce, test, and evaluate a small-scale physical model of a mobile work platform lift under predetermined operational conditions. The project involved conceptualization, simulation, optimization, selection of materials and components, production, assembly, and experimentation. This paper provides a comprehensive account of the project, including the design process, the structural analysis methods used to evaluate the safety and performance of the design, the production and assembly processes, and the experimental results of the physical model. The interdisciplinary approach used in the project is discussed, and the project outcomes, achievements, and challenges encountered are reflected upon. The project-based learning approach provides an effective way to develop and apply engineering skills in a real-world context, and this didactical instrument can serve as a guide for other educators and students in similar endeavors.
Keywords: Integrated project-based learning, Mobile work platform lift, Structural analysis, Interdisciplinary engineering education, Small-scale physical model.

INTRODUCTION

Mechanical engineering is an essential discipline that has contributed significantly to the advancement and betterment of society. The field of mechanical engineering deals with the design, analysis, and manufacturing of mechanical systems and devices that are used in various industries, including automotive, aerospace, energy, healthcare, and construction, among others. Mechanical engineers are responsible for developing and improving the performance, efficiency, and reliability of machines, systems, and processes that drive modern society.

Mechanical engineering plays a critical role in the development of new technologies that improve the quality of life, enhance productivity, and reduce environmental impact. For example, advances in this area have led to the development of cleaner and more efficient energy systems, such as wind turbines, solar panels, and fuel cells, that can help reduce our dependence on fossil fuels and mitigate climate change. Mechanical engineering has also contributed to the design and production of medical devices and prosthetics that improve the health and well-being of people around the world. In addition, it has has enabled the development of advanced transportation systems, such as electric and autonomous vehicles, that offer safer, more comfortable, and more sustainable mobility options for people and goods. Therefore, mechanical engineering is a vital discipline that has played and will continue to play a crucial role in shaping the future of society.

Known as a broad field that encompasses a range of subjects that are interconnected and interdependent, some of the typical subjects in mechanical engineering include machine design, solid mechanics, materials science, thermodynamics, fluid mechanics, heat transfer, control systems, and manufacturing processes, among others. These subjects provide a foundation for understanding the behavior of mechanical systems and devices, and for developing solutions to engineering problems.

The subjects in mechanical engineering interact with each other in several ways. For example, machine design involves the application of solid mechanics, materials science, and manufacturing processes to develop mechanical systems that meet specific requirements for functionality, durability, and safety. The performance of the designed systems is evaluated using concepts from fluid mechanics, heat transfer, and thermodynamics to ensure that they operate efficiently and effectively. Control systems are used to regulate the behavior of mechanical systems, such as robots, vehicles, and machines, to achieve desired outcomes. Materials science is also critical to mechanical engineering, as the properties of materials used in mechanical systems, such as strength, stiffness, and fatigue resistance, directly affect their performance and durability. Therefore, a strong foundation in all of these subjects is necessary to become a competent mechanical engineer capable of designing, analyzing, and manufacturing mechanical systems that meet the needs of modern society.

Project-Based Learning (PBL) is an important pedagogical approach in the field of mechanical engineering education, as it helps students develop practical skills and experience through hands-on projects. In order to prepare students for the challenges of real-world engineering projects, it is essential that undergraduate mechanical engineering courses include opportunities for PBL.

One example of a subject that can provide such opportunities is Integrated Project, which is offered as part of the mechanical engineering curriculum at many universities. This subject is typically designed to challenge students to work collaboratively in teams to design, build, and test a functional engineering system or device. By engaging in this kind of PBL activity, students can develop a range of practical skills, including project management, problem-solving, critical thinking, and communication, all of which are essential for success in the engineering profession.

The design, simulation, production, and testing of a mobile work platform lift is a challenging and interdisciplinary project that requires a wide range of engineering skills. In this paper, we present an integrated project-based learning approach to designing and testing a small-scale mobile work platform lift. The project was assigned to the students as the final work in the Integrated Project subject, which required the application of various concepts and theories from prerequisite subjects, including machine design, solid mechanics, computational solid mechanics, finite element method, elastic theory, materials science, strength of materials, system control, dynamics, and technical drawing.

The objective of the project was to design, simulate, produce, test, and evaluate a small-scale physical model of a mobile work platform lift. The notice given to the students at the beginning of the semester specified the load, maximum dimensions, the lifting speed, and some system control details. The students were divided into groups to work collaboratively on the one semester project. The 6 months project involved conceptualization, simulation, optimization, selection of materials and components, production, assembly, and experimentation.

LITERATURE REVIEW

In this section we summarize relevant concepts and theories from the prerequisite subjects that were applied in the project. We also discuss previous research on mobile work platform lifts, including design considerations, structural analysis, and performance evaluation. The literature review was conducted through a comprehensive search of scientific databases to identify relevant technical articles related to the research theme. To streamline and expedite the process, artificial intelligence tools were utilized to assist in identifying, sorting, and selecting literature, as well as supporting the writing process of this article.

MECHANICAL ENGINEERING COURSE AT CENTRO UNIVERSITÁRIO FEI

According the official site (https://portal.fei.edu.br/), Centro Universitário FEI (FEI) is a well-respected Brazilian private university center located in the city of São Bernardo do Campo. Founded in 1941, FEI has a long-standing reputation for providing high-quality education in engineering, business, and technology. The university is known for its commitment to innovation and excellence in teaching, research, and community engagement.

The former Faculty of Industrial Engineering - FEI, and the Higher School of Business Administration - ESAN, were born from the intuition and courage of Fr. Roberto Sabóia de Medeiros, SJ (1905-1955) a visionary Jesuit who, in the early 1940s, foreseeing economic growth and the need for engineers and managers that Industry and the Country would need, founded both institutions.

FEI offers several engineering courses at both the undergraduate and graduate levels. The undergraduate engineering programs include Mechanical Engineering, Electrical Engineering, Computer Engineering, Chemical Engineering, Civil Engineering, and Production Engineering. The programs are designed to provide students with a solid foundation in engineering principles and practices, as well as hands-on experience in the field. FEI's commitment to providing quality education and research opportunities has made it a leading institution in the region and a top choice for students interested in pursuing careers in engineering and related fields.

FEI has a long-standing tradition of

producing highly skilled mechanical engineers who have gone on to make significant contributions to their field. Over the years, many of the university's graduates have become leaders in the engineering industry, both in Brazil and around the world. These alumni have brought their expertise and knowledge to a wide range of sectors, from automotive and aerospace to energy and manufacturing.

One of the hallmarks of FEI's mechanical engineering program is its strong focus on practical applications. The program provides students with a rigorous theoretical foundation in engineering principles, but also emphasizes the importance of real-world applications and problem-solving. This approach has helped to produce graduates who are well-prepared for the challenges of the engineering profession, and who are able to hit the ground running in their careers.

FEI's alumni network is also an important part of the university's tradition in mechanical engineering. Graduates of the program have formed a tight-knit community of professionals who are dedicated to advancing the field of engineering and supporting one another in their careers. Many of these alumni have gone on to become mentors to current students, sharing their knowledge and experience and helping to shape the next generation of mechanical engineers.

The mechanical engineering course at FEI is a rigorous program that is designed to prepare students for a wide range of careers in the engineering field. The course is offered in two formats: a 10-semester day course and a 12-semester night course. Regardless of which format students choose, they will complete a total of 4,133 class hours, which includes both theoretical and practical coursework.

In addition to the class hours, students in the mechanical engineering program are required to complete 100 hours of complementary activities, which may include research projects, technical visits, and other forms of practical experience. This component of the program is designed to help students develop a well-rounded set of skills and gain exposure to different areas of the engineering field.

Finally, all students in the mechanical engineering program are required to complete a supervised internship of 160 hours, which provides an opportunity to apply their skills in a real-world setting and gain valuable professional experience. Overall, the mechanical engineering program at FEI represents a significant commitment of time and effort, with a total workload of 4,393 hours. However, for students who are passionate about engineering and dedicated to their studies, the rewards of this program can be significant, opening up a wide range of exciting career opportunities in the field of mechanical engineering. The mechanical engineering program is depicted in Figure 1.

The Mechanical Engineering course has three disciplines that act as Integrated Projects. Each Integrated Project discipline has a different emphasis, respectively Prototyping, Thermo-fluid Systems, and Mechanical Systems. The arrows demonstrate the direct connection between the previous disciplines and the Integrated discipline. The red oval demonstrates at which position in the curriculum matrix, the Integrated Project discipline with an emphasis on mechanical systems is located. This paper refers to this specific subject.

INTEGRATED PROJECT SUBJECT WITH EMPHASIS ON MECHANICAL SYSTEMS

The subject's syllabus includes the following topics.

a) Fundamentals of mechanical system design: structural, mechanical, and electrical design projects, compliance

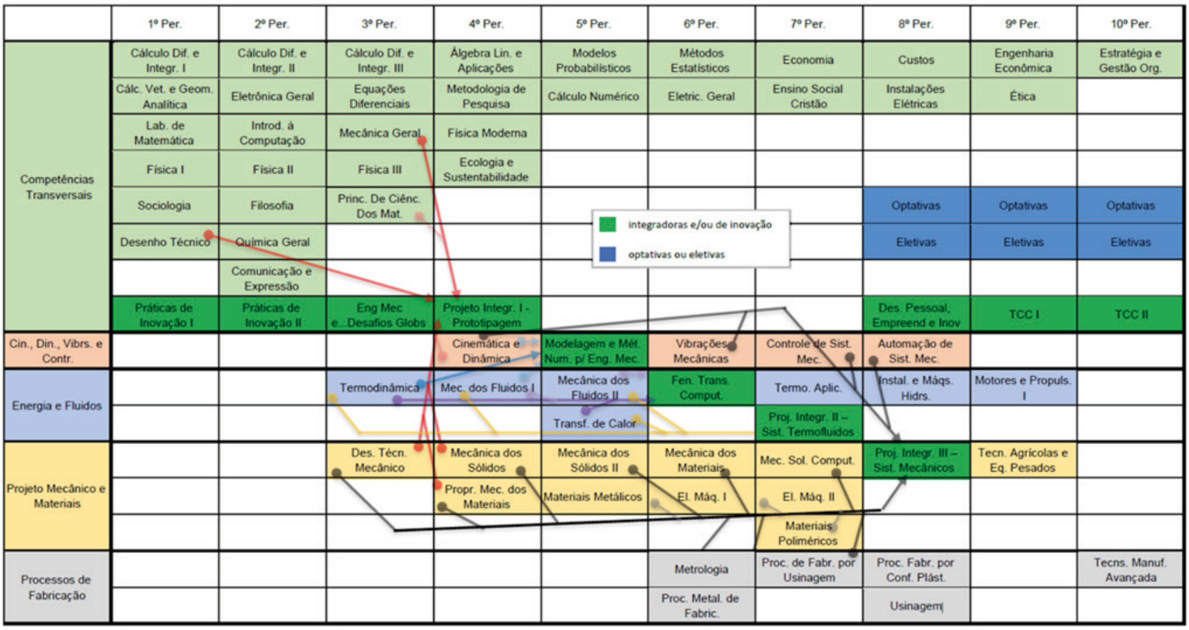
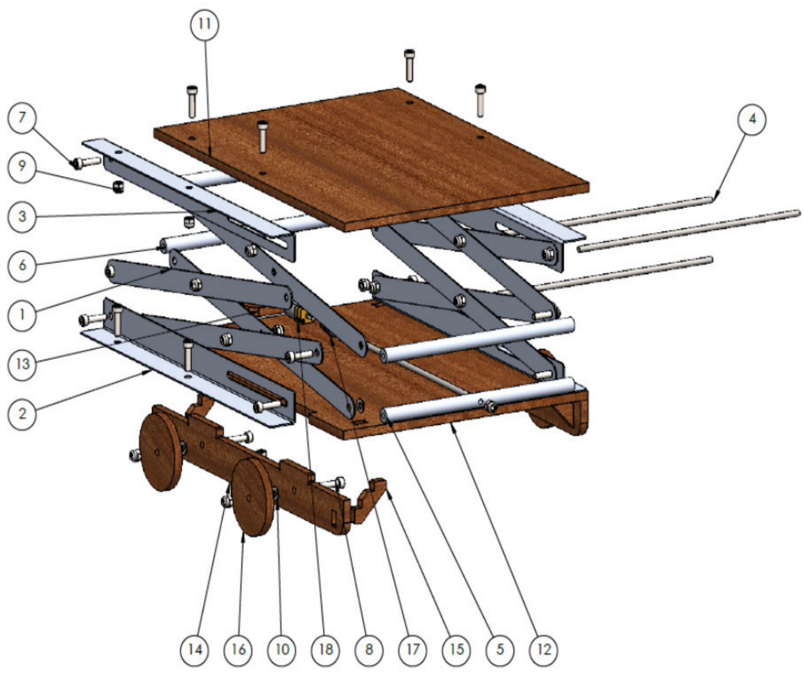


Figure 1 - Mechanical Engineering course structure



ITEM	Part Number	QTY.
1	TRELIÇA - ALUMÍNIO 1060	8
2	SUPORTE LATERAL ESQUERDA - ALUMÍNIO 1060	2
3	SUPORTE LATERAL DIREITA - ALUMÍNIO 1060	2
4	BARRA ROSCADA ZINCADA BRANCA M4 - AISI 304	4
5	BARRA REDONDA MACIÇA 3/8" - ALUMÍNIO 6063-T6	1
6	BARRA REDONDA MACIÇA 3/8" - ALUMÍNIO 6063-T6	3
7	PARAFUSO CABEÇA SEXTAVADA INTERNA - M4x16 - DIN 912 - ZINCADO BRANCO	18
8	PARAFUSO CABEÇA SEXTAVADA INTERNA - M4x20 - DIN 912 - ZINCADO BRANCO	4
9	PORCA SEXTAVADA COM INSERTO DE NYLON - M4 - ISO 7040 - ZINCADO BRANCO	27
10	ARRUELA LISA - M4 DIN 125 - ZINCADO BRANCO	8
11	BASE INFERIOR - MDF 6mm	1
12	BASE INFERIOR - MDF 6mm	1
13	BASE DO MOTOR - MDF 6mm	1
14	ABA LATERAL - MDF 6mm	2
15	CANTONEIRA DE REFORÇO - MDF 6mm	4
16	RODA - MDF 6mm	4
17	ACOMPLAMENTO - ABS	1
18	MOTOR DC 6V - 500RPM - 200gf.cm	1

Figure 5 - Lifting platform exploded view and bill of materials

with design standards, ergonomics, hygiene, and safety.

b) Electric drives and types of motors, service factor, inertia, brakes, and sensors.

c) Reliability and maintenance: concepts of reliability applied to products and maintenance, including parameter estimation, accelerated testing, and time/failure rate.

d) Practical project: applies competencies in solid mechanics, machine elements, materials, kinematics, dynamics, vibrations, and control, as well as manufacturing processes, design, project implementation, and a mechanical system that solves a given problem and includes structure, drives, automatic control, and sensing. Computational practices for building the designed device and performance testing that corroborates analytical and computational predictions.

e) Conclusions: summary of the key concepts covered in the subject and reflection on the practical applications of mechanical system design.

The subject objectives are:

a) Recall fundamental concepts presented in mechanics of solids, machine elements, kinematics, dynamics, electrical drives, and manufacturing processes.

b) Implement computational methodologies for analysis and project development.

c) Design and manufacture electromechanical devices.

d) Interpret, analyze, and critically evaluate the results of the models and prototypes developed, demonstrating an understanding of the limitations resulting from the restrictions and simplifying assumptions employed.

e) Develop problem-solving skills requiring creativity and mastery of the innovative process, using technology in a multidisciplinary way, conceiving, developing, implementing, and disseminating innovative technologies and solutions, with an entrepreneurial and flexible attitude.

f) Learn autonomously, to deal with complex situations and contexts, updating themselves regarding advances in science and technology.

g) Work and lead multidisciplinary teams, interacting with people and diverse cultures, being able to understand, respect, and value differences.

h) Communicate effectively and efficiently in written, oral, and graphic forms.

i) Analyze and understand the demand and users of engineering solutions and their context to formulate questions and design mechanical engineering solutions.

j) Conceive, design, and analyze systems, products (goods and services), components, or processes within the scope of Mechanical Engineering.

k) Develop, identify, validate, and apply models for optimization and problem-solving within the scope of Mechanical Engineering.

The following teaching and learning methodologies are employed during this course:

a) Lectures;

b) Group activities;

c) Use of computer systems;

d) Case studies;

e) PBL.

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f) The subject´s milestones are:

g) Project conception

h) Initial design (material selection and sizing)

i) Decision matrix development

j) Virtual prototyping (3D CAD model and technical drawings)

k) Computer-aided simulation (CAE)

l) Manufacturing of the first prototype

m) Proposal for improvements (design spiral)

n) Manufacturing and testing of the final prototype

o) Presentation of the final prototype

p) Final comprehensive report

PROJECT-BASED LEARNING

Project-based learning (PBL) is an educational approach that emphasizes active learning through the completion of real-world projects. In contrast to traditional lecture-based methods, PBL engages students in hands-on experiences that require them to apply their knowledge, problem-solving skills, and critical thinking abilities (RIO; RODRIGUEZ, 2022). By working on projects that mimic real-world scenarios, students are able to develop a deeper understanding of the subject matter and gain practical skills that are transferable to their future careers (CHUA *et al.,* 2013). PBL has been widely recognized as an effective pedagogical strategy across various disciplines, including engineering education (MALIK; ZHU, 2022).

One of the key benefits of project-based learning is its ability to foster interdisciplinary collaboration. In today's complex and interconnected world, many real-world problems require expertise from multiple disciplines (WU *et al.*, 2021). PBL provides a platform for students from different backgrounds, such as mechanical engineering, electrical engineering, and materials science, to collaborate and contribute their unique perspectives and skills to a shared project (PINDADO *et al.*, 2018). This interdisciplinary approach not only enhances the learning experience but also prepares students for the challenges they will encounter in their professional careers, where teamwork and collaboration across disciplines are often required (CEH-VARELA *et al.*, 2023).

Through project-based learning, students are not just passive recipients of knowledge but active participants in the learning process. They become self-directed learners who take ownership of their education (BERSELLI *et al.*, 2020). According to M., Kaushik (2020), in a project-based learning environment, students are tasked with defining the project objectives, conducting research, identifying resources, and making informed decisions (HAN *et al.*, 2014). This autonomy and responsibility promote a sense of ownership and motivation, as students see the direct relevance and application of their efforts (SANJEEV *et al.*, 2022). They become more engaged and invested in their learning, leading to deeper comprehension and long-lasting knowledge retention (SALAZAR-PEÑA *et al.*, 2023).

Moreover, project-based learning allows students to develop a range of essential skills beyond the technical knowledge of their field (MILLER; KRAJCIK, 2019). These skills include communication, problem-solving, critical thinking, creativity, and time management (TSENG *et al.*, 2011). Working on projects necessitates effective communication and collaboration with peers and instructors, as well as the ability to analyze complex problems and devise innovative solutions (MONTEQUÍN *et al.*, 2012). Students also learn to manage their time efficiently to meet project deadlines, mirroring the demands of real-world projects (VANASUPA *et al*., 2007). These transferrable skills acquired through project-based learning are highly valued by employers and contribute to students' overall professional development (YOUNG *et al*., 2021).

Research has shown the positive impact of project-based learning on student learning outcomes (FRANK; LAVY; ELATA, 2003). Studies have demonstrated improved student performance in areas such as problem-solving, critical thinking, and retention of knowledge compared to traditional instructional approaches (LIN *et al*., 2021). Furthermore, students often report higher levels of satisfaction and engagement when participating in project-based learning experiences (GIL, 2017). The integration of theory and practice in a meaningful context enhances students' motivation, promotes deeper understanding, and prepares them for the complexities of the professional world (KUPPUSWAMY; MHAKURE, 2020).

MOBILE WORK PLATFORM LIFT

Mobile work platform lifts, also known as aerial work platforms or elevated work platforms, are specialized equipment designed to provide temporary access and a safe working platform at elevated heights. These lifts are commonly used in various industries, including construction, maintenance, manufacturing, and warehousing, to facilitate tasks such as installation, inspection, repair, and maintenance at elevated locations. Mobile work platform lifts offer advantages over traditional scaffolding or ladders by providing a stable and adjustable platform that can be easily maneuvered to different work areas, increasing efficiency and safety (KAYHANI *et al.*, 2021). Examples of hydraulic cylinder mobile work platform lifts are shown in Figure 2.

Figure 2 - Hydraulic cylinder mobile work platform lifts: (a - left) two hydraulic cylinders driving type platform; (b - rigth) one hydraulic cylinder driving type platform (HONGYU; ZIYI, 2011)

The design and development of mobile work platform lifts involve considerations of structural integrity, stability, lifting mechanisms, control systems, and safety features. The structural design must be capable of supporting the weight of workers, tools, and equipment while maintaining stability and withstanding external forces, such as wind or vibrations (AUGUSTYN *et al*., 2023). The lifting mechanisms may include hydraulic, pneumatic, or electric systems, each with its own advantages and limitations. Control systems enable operators to maneuver the lift, adjust platform height, and ensure safe operation (OLTEAN, 2019). Safety features such as guardrails, emergency stop buttons, and overload protection are essential to prevent accidents and ensure worker safety (PARAMASIVAM *et al*., 2021).

Various types of mobile work platform lifts exist, including scissor lifts, boom lifts, and personnel lifts, each suited for specific applications and environments. Scissor lifts feature a folding, crisscrossing mechanism that extends vertically, providing a stable platform. Boom lifts, on the other hand, use a hydraulic arm or articulated boom to extend horizontally and vertically, offering increased reach and maneuverability (PIN; CULIOLI, 1992). Personnel lifts are compact lifts designed for single-worker tasks and are often lightweight and easy to transport. The choice of the appropriate lift depends on factors such as required working height, reach, terrain conditions, and the nature of the tasks to be performed (ZHU *et al.*, 2023).

The design and operation of mobile work platform lifts are subject to various international and regional safety standards and regulations. Organizations such as the Occupational Safety and Health Administration (OSHA) in the United States and the European Union Machinery Directive provide guidelines and requirements for the safe use of these lifts. Compliance with these standards is crucial to ensure operator and worker safety, minimize the risk of accidents, and promote best practices in the industry. Manufacturers and designers of mobile work platform lifts need to consider these standards during the design and production stages (CIUPAN *et al.*, 2019).

Advancements in technology have led to the development of innovative features and functionalities in mobile work platform lifts. These include self-leveling systems, automated controls, advanced safety sensors, and telematics. Self-leveling systems enable the lift to automatically adjust its position and orientation on uneven surfaces, maintaining stability and ensuring a level working platform (PASCALE *et al.*, 2006). Automated controls allow for precise and intuitive operation, enhancing efficiency and ease of use. Advanced safety sensors detect potential hazards, such as obstructions or uneven ground, and alert the operator, contributing to accident prevention. Telematics systems enable remote monitoring of lift performance, maintenance scheduling, and data collection for analysis and optimization (SON *et al.*, 2022).

The use of mobile work platform lifts offers numerous benefits in terms of productivity, efficiency, and safety in various industries (MICHAUD *et al.*, 2005). These lifts provide workers with a secure and stable platform at elevated heights, allowing them to perform tasks more effectively and comfortably. With their mobility and versatility, mobile work platform lifts can access areas that may be difficult to reach using other means, thus improving productivity and reducing downtime (ZðÑIGA-AVILÉS *et al.*, 2014). Additionally, these lifts minimize the risk of falls and other accidents associated with working at heights, ensuring a safer working environment for operators and workers (STAWIńSKI *et al.*, 2019).

METHODOLOGY

The project focused on designing and testing a small-scale mobile work platform lift within the context of an integrated project-based learning approach. The objective of the project was to provide Mechanical Engineering students with a hands-on experience that required the application of various concepts and theories from prerequisite subjects. The project aimed to design, simulate, produce, test, and evaluate a functional physical model of a mobile work platform lift under predetermined operational conditions.

The integrated project-based learning approach was implemented as the primary instructional method for the project. It involved assigning the project as the final work in the Integrated Project subject, where students were required to work collaboratively in interdisciplinary teams. This approach provided a real-world context for students to develop and apply their engineering skills, promoting active learning, problem-solving, and critical thinking.

The integrated project-based learning

approach played a crucial role in the design and testing process of the small-scale mobile work platform lift. By incorporating various concepts and theories from prerequisite subjects, students were able to apply their theoretical knowledge to practical engineering challenges. The project required them to navigate through the entire design process, including conceptualization, simulation, optimization, material and component selection, production, assembly, and experimental testing.

Throughout the project, students were encouraged to collaborate, communicate, and think critically to overcome obstacles and make informed design decisions. The interdisciplinary nature of the project enabled students to integrate different engineering disciplines, such as mechanical engineering, structural analysis, and materials science, to develop a comprehensive and well-rounded solution.

The integrated project-based learning approach also provided students with opportunities to enhance their problem-solving skills, creativity, and innovation. By working on a real-world project, they were exposed to the complexities and challenges that engineers face in practice. This approach fostered a deeper understanding of engineering principles and their practical applications.

Additionally, the project-based learning approach promoted a holistic view of the design and testing process. Students were encouraged to consider not only the technical aspects of the mobile work platform lift but also its safety, performance, and usability. This comprehensive approach ensured that the final design solution met the predetermined operational conditions and performance requirements.

During the writing process of this article, artificial intelligence (AI) tools were employed to facilitate various aspects of the literature review and writing process. AI tools were utilized to search, identify, select, and review relevant literature from the main technical databases. These tools efficiently scanned through vast amounts of scholarly articles, conference papers, and research publications to identify sources that align with the research topic and keywords. By leveraging AI algorithms and natural language processing capabilities, these tools aided in the extraction of key information and insights from the selected literature, streamlining the review process.

Furthermore, AI tools played a significant role in reviewing the writing itself. They were employed to enhance the readability, coherence, and grammatical accuracy of the manuscript. AI-powered language models were utilized to identify potential improvements in sentence structure, grammar, and word choice, ensuring a more polished and professional writing style. These tools also provided suggestions for clarifying ambiguous or convoluted sentences, improving the overall clarity and precision of the article.

The use of AI tools in the literature review and writing process offered several benefits. Firstly, it expedited the literature search and review process, saving considerable time and effort. The AI tools efficiently filtered and ranked relevant sources, enabling the authors to focus on the most influential and pertinent research. Additionally, the AI tools facilitated the identification of knowledge gaps and emerging trends within the field, aiding in the formulation of well-informed arguments and conclusions.

Moreover, the integration of AI tools in the writing process enhanced the overall quality of the article. By leveraging advanced language processing capabilities, the tools assisted in refining the structure, grammar, and coherence of the manuscript, ensuring a more concise and professional presentation of the research findings. This AI-assisted approach resulted in a more polished and refined final document.

It is worth noting that while AI tools provided valuable support throughout the article writing process, they were utilized as aids to the authors' expertise and judgment. The final decisions regarding literature selection and writing style were ultimately made by the authors, who carefully reviewed and refined the content in collaboration with the AI tools.

Overall, the integrated project-based learning approach enhanced the students' learning experience by providing them with a practical, interdisciplinary, and collaborative environment. It allowed them to apply their theoretical knowledge, develop engineering skills, and gain insights into the complexities of designing and testing a small-scale mobile work platform lift. The outcomes of this approach contributed to the successful completion of the project and provided valuable lessons and experiences that can guide future educators and students in similar endeavors.

RESULTS AND DISCUSSIONS

In this section, we present the results and discussions of the mobile work platform lift project developed by the student groups in the Integrated Project course.

DESIGN

The student group used computer-aided design (CAD) software to develop the 3D models of the mobile work platform lift. The design process involved selecting appropriate materials, defining the geometry of the parts, and considering manufacturing constraints.

In the previous stages of the project, the scissor model of a Mobile Work Platform Lift (MWPL), also known as the pantograph model, was selected. This model is the most suitable for construction as it offers greater structural simplicity and is ideal for lifting heavier loads. Although it does not have many degrees of freedom, this project does not require such application.

The group developed a simplified structural design of the lifting platform for this project, using only two pairs of trusses. The design of the structure created by the group can be observed in Figure 3.

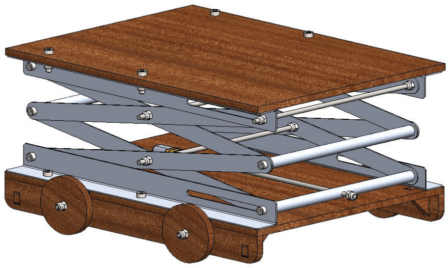

Figure 3 - Simplified structural design of the lifting platform

The operating principle of the scissor platform is based on the opening and closing of the truss bases, resulting in a change in angle capable of raising or lowering the platform along the trusses. Thus, it becomes possible to raise or lower loads. Figure 4 demonstrates the operation of the developed platform, with its elevation achieved by the closing of the links and the increase in the internal angles of the trusses.

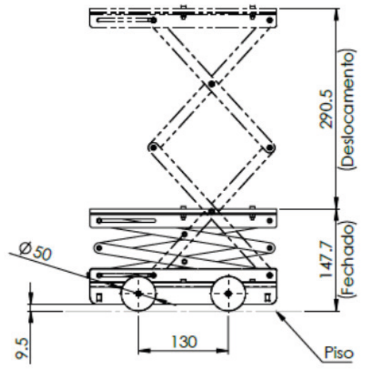

Figure 4 - Lifting platform operation

There are various ways to achieve this movement between the bases to generate height variation. In industrial platforms, this can be accomplished through electric or combustion motors that rotate a screw to move the links apart or together, or even by hydraulic actuators that push and retract the links. However, for smaller scales and simpler designs, this movement can be achieved using cranks that lift the platform. For the development of the initial prototype, the group selected the operation through an electric motor, which would rotate a shaft capable of moving the truss links apart or together, resulting in the elevation of the platform, as presented in Figure 5.

The next step towards finalizing the project involved implementing the identified improvements in the prototype. The devised improvements included eliminating the clearances in the prototype to reduce platform instability and lubricating the contact points to minimize friction.

For the project, the development of a position and velocity control system was planned. This involved integrating an electric motor with an ultrasonic sensor to send position data of the moving part of the platform to a program developed in Arduino. The program would perform the necessary calculations and incorporate a closed-loop PID control system. Although both the code and electronic assembly of the required circuit were completed, it was found that the purchased electric motor did not possess sufficient torque to lift the load. Consequently, to fulfill the project requirements, a control loop was developed using Simulink to simulate the conditions of the actual platform, along with the physical prototype of the developed control system. The design was evaluated in terms of strength, stiffness, and weight, using finite element analysis (FEA) software.

SMALL SCALE MODEL ASSEMBLY

For the assembly of the work platform model, three types of manufacturing processes were utilized to produce the components of the assembly. The laser cutting machine available in the workshop of the FEI University Center was used for the MDF items, including the lower base, upper base, side supports for wheels, wheels, and corner brackets. Additive manufacturing (polymer 3D printing) was employed for the coupling of the power transmission shaft and electric motor. The items produced using these two processes are shown in Figure 6.

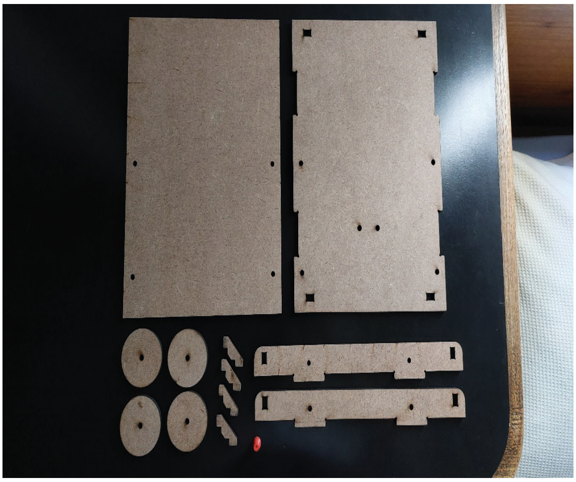

Figure 6 - Lifting platform Components produced through laser cutting and 3D printing

In the case of aluminum items, the waterjet cutting process was employed for fabrication. The waterjet cutting machine available in the workshops of the FEI University Center was used for this purpose. For the bent pieces, the sheet metal bending tool, also available in the institution, was used. The components produced through these processes are presented in Figure 7.

Figure 7 - Lifting platform Xomponents produced through waterjet cutting and bending

The bars that interconnect the set of trusses underwent the process of bandsaw cutting, with a 3 mm diameter hole drilled on both opposing faces, followed by manual threading with an M4 tap. To ensure safety during assembly, the sharp edges were chamfered with the aid of a grinder. All procedures were carried out within the facilities of the Mechanical Laboratories Center at the FEI University Center, utilizing the tools available in the workshops. Some of the components produced in this stage are illustrated in Figure 8.

Figure 8 - Lifting platform Interconnecting bars produced for prototype assembly

With all the produced and purchased components at hand, the assembly of the platform began with the support base of the assembly. Instant wood adhesive with the application of a catalyst for accelerating the bonding process was used to join the MDF components. The aluminum side supports, as assembled in Figure 9, were fixed to the MDF base using screw connections with M4 screws, washers, and nuts.

Figure 9 - Assembly of the lifting platform support base

After completing the support base, the assembly of the truss sets that provide load support and enable platform elevation was carried out. The trusses were assembled in a scissor (pantograph) pattern with interconnecting bars at three support points: at both ends and in the center for enhanced structural stability. The trusses are joined with the interconnecting bars using M4 screws and washers threaded directly into the holes. Figure 10 illustrates the assembly process of the trusses and interconnecting bars.

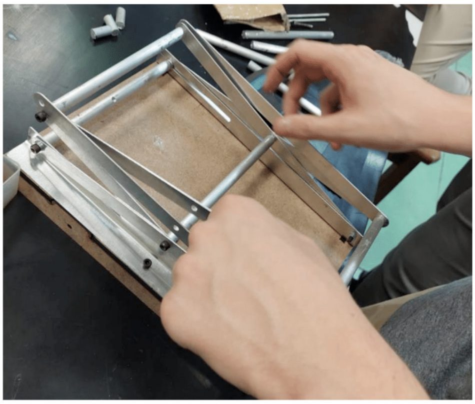

Figure 10 - Assembly of the designed lifting platform trusses

Following the assembly of the trusses, the upper base was fixed to allow for the positioning of the load to be lifted. Similar to the lower base, one of the trusses is fixed to a hole to serve as a pivot point, while the other truss is aligned with the slots on the aluminum side supports to serve as a guide for the vertical movement of the platform. Once again, M4 screws, nuts, and washers were used to secure the components. Figure 11 illustrates the partially completed platform, including the assembly of the upper load base as described earlier.

Figure 11 - Partially completed lifting platform with the assembly of the upper base

The assembly of the platform is completed with the inclusion of wheels, making it mobile and meeting the project requirements and classification as a Mobile Work Platform Lift (MWPL). The four wheels are positioned in the holes on the lower base and secured with M4 screws and nuts. The tightness is reduced to prevent locking during rotation. Thus, the complete assembly of the designed platform is presented in the following figures, which showcase almost all the components used in the assembly.

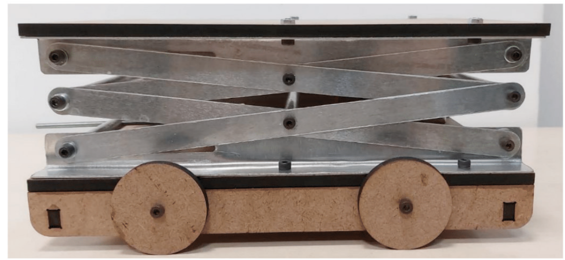

Figure 12 - Side view of the fully assembled lifting platform

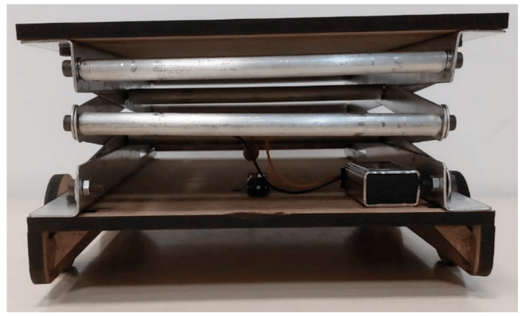

Figure 13 - Front view of the fully assembled lifting platform

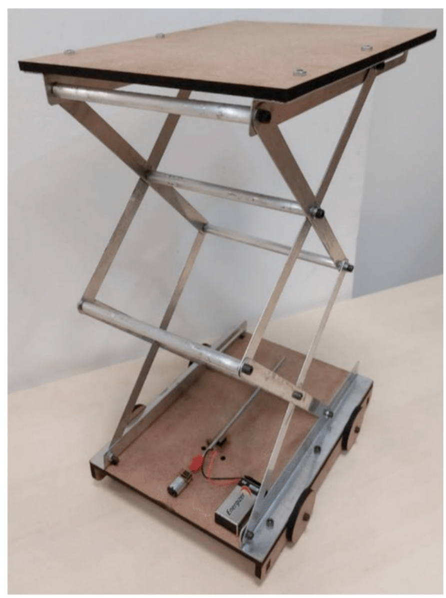

Figure 14 - View of the fully assembled lifting platform in the maximum height condition

With the platform completed, tests were conducted to verify the operation of the lifting mechanism. Initially, manual tests were performed, which confirmed the correct functioning as expected. Subsequently, a manual screwdriver with an M4 threaded rod attached to its tip was used to simulate the operation as intended for the use of an electric motor. The threaded rod is first screwed into the center of the interconnecting bar in the oblong region of the lower base, and then the screwdriver is activated in the upward direction to lift the platform. The direction of the screwdriver is then reversed to allow descent. A demonstration video of the operation in the initial condition of the platform was recorded and is available at the following link: https://youtu.be/4Cy0okNGpFY.

The verification of the load requirement to be supported by the platform involved a static load positioning test at the maximum height of the platform. A mass of 3.048 kilograms was used for the test, which exceeds the maximum operational condition specified in the project, approximately 2 kilograms. The measurement of the mass used for the load test is shown in Figure 15.

Figure 15 - Measurement of the mass used for the load test on the constructed platform

The platform was able to sustain the mass under the described condition without suffering any damage or structural failure, as demonstrated in Figure 16. This indicates that it is suitable for load lifting tests.

Figure 16 - Demonstration of the static load test at the maximum height condition of the lifting platform

Despite both tests being successful, points for improvement and attention were noted, such as the need to enhance the stability of the structure to prevent horizontal movements and load tipping, as well as the need to reduce the effort required for lifting. In this stage of the project, improvements were implemented in the prototype to optimize the lifting capacity of the platform.

The first improvement implemented was tightening the M4 screws that connect the truss sets, as their clearance was causing instability in the structure during lifting. This improvement reduced horizontal movements of the structure and the inclination of the upper support base, preventing load tipping. Another aspect addressed in the structure was lubricating the contact points between the trusses and the guide oblongs to reduce friction between components. This resulted in a reduced force required for load lifting, making the structure more efficient.

SIMULATION

The FEA software was used to simulate the behavior of the mobile work platform lift under different loads and operating conditions. The simulations were used to optimize the design and identify potential failure modes. The results of the simulations were compared to the experimental data obtained during the testing phase.

The structural simulations were performed using SolidWorks Simulation software. This decision was made based on the fact that the initial analysis yielded satisfactory results regarding the behavior of the structure, ensuring that the group could assemble the lift platform without risks of breakage or failure when supporting the 2 kg load on its upper base. The properties used in the simulations are presented in Figure 17.

An illustration of the original geometry of the lift platform is shown in Figure 18.

Figure 18 - Lifting platform geometry model

It is observed that despite the reduction in simplifications, there are still structures that would only hinder result interpretation and increase computational time if not disregarded, such as the motor responsible for the movement of the structure. As mentioned above, the finite element mesh was refined following the same model as the first analysis. The generated mesh for this simulation contains elements of various sizes, as illustrated in Figure 19.

It can be noted that the largest element measures 13.21 mm, while the smallest element measures 1.06 mm. Therefore, the finite element mesh obtained a quality classified as high, thereby facilitating mathematical convergence and achieving better results. The finite element mesh is presented in Figure 20.

Figure 20 - Finite element mesh used in the structural simulation of the lift platform

With the addition of new components to the geometry being analyzed, some contact definitions needed to be updated to be compatible with the structure's requirements and boundary conditions. It is worth noting that the Bonded contact type, used in structures that need to be interpreted as being stuck together (without sliding), was not changed. Therefore, linear results were also expected for this simulation. Figure 21 presents the contact information implemented during the definition of the boundary conditions.

Considering the goal of improvement through enhanced analysis, the material definitions remained the same, as in the

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Study Properties

Study name	Static 1
Analysis type	Static
Mesh type	Mixed Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	Automatic
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (C:\Documentos\1. FEI\FEI 2023\Projeto Integrador)

Figure 17 - List of properties used in the structural simulations

Mesh information

Mesh type	Mixed Mesh
Mesher Used:	Curvature-based mesh
Jacobian points for High quality mesh	16 Points
Jacobian check for shell	On
Maximum element size	13,2055 mm
Minimum element size	1,05644 mm
Mesh Quality	High
Remesh failed parts independently	Off

Mesh information - Details

Total Nodes	670255
Total Elements	401148
Time to complete mesh(hh;mm;ss):	00:00:27
Computer name:	

Figure 19 - Lifting platform mesh information

Contact Information

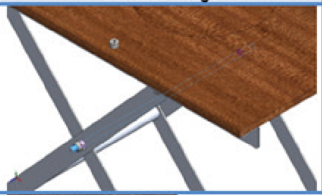
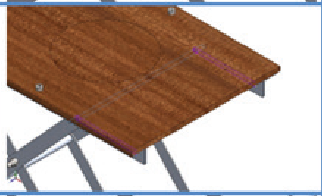
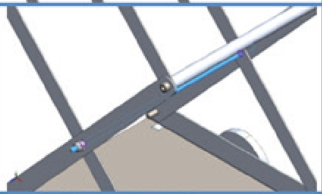
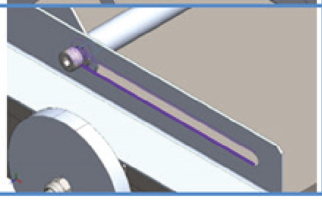
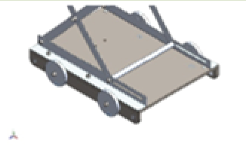
Contact	Contact Image	Contact Properties
Local Interaction-70		**Type:** Bonded interaction pair **Entities:** 3 face(s)
Local Interaction-136		**Type:** Bonded interaction pair **Entities:** 9 face(s)
Local Interaction-137		**Type:** Bonded interaction pair **Entities:** 5 face(s)
Local Interaction-138		**Type:** Bonded interaction pair **Entities:** 6 face(s)

Figure 21 - Information regarding contact definitions and type used

Curve Data:N/A		
	**Name:**	6063-T6
	Model type:	Linear Elastic Isotropic
	Default failure criterion:	Unknown
	Yield strength:	2,15e+08 N/m^2
	Tensile strength:	2,4e+08 N/m^2
	Elastic modulus:	6,9e+10 N/m^2
	Poisson's ratio:	0,33
	Mass density:	2.700 kg/m^3
	Shear modulus:	2,58e+10 N/m^2
	Thermal expansion coefficient:	2,3e-05 /Kelvin

Figure 22 - Mechanical properties of the materials used in the analysis

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
On Cylindrical Faces-1		Entities: 4 face(s) Type: On Cylindrical Faces Translation: 0; ---; --- Rotation: ---; ---; --- Units: mm; rad

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-0,505865	81,7044	9,06976e-14	81,7059
Reaction Moment(N.m)	0	0	0	1e-33

Fixture name	Fixture Image	Fixture Details
On Flat Faces-2		Entities: 2 face(s) Type: On Flat Faces Translation: ---; ---; 0 Rotation: ---; ---; --- Units: cm; rad

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	0,526251	0	0	0,526251
Reaction Moment(N.m)	0	0	0	1e-33

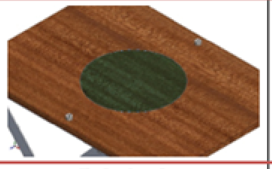
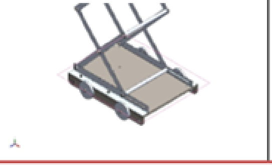
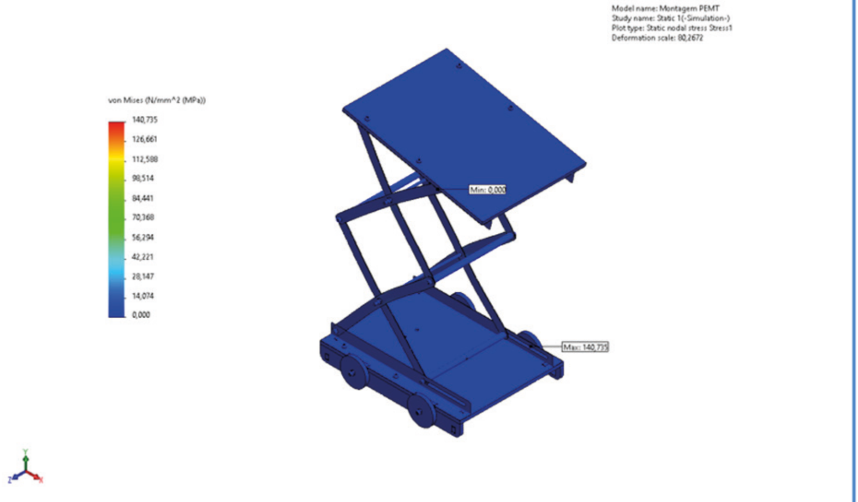
Load name	Load Image	Load Details
Force-1		Entities: 1 face(s) Type: Apply normal force Value: 20 N
Gravity-1		Reference: Top Plane Values: 0 0 -9,81 Units: m/s^2

Figure 23 - Boundary conditions for force and fixation of the analyzed structure

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0,000N/mm^2 (MPa) Node: 85919	140,735N/mm^2 (MPa) Node: 665414



Montagem PEMT-Static 1-Stress-Stress1

Figure 24 - von Mises stresses plot

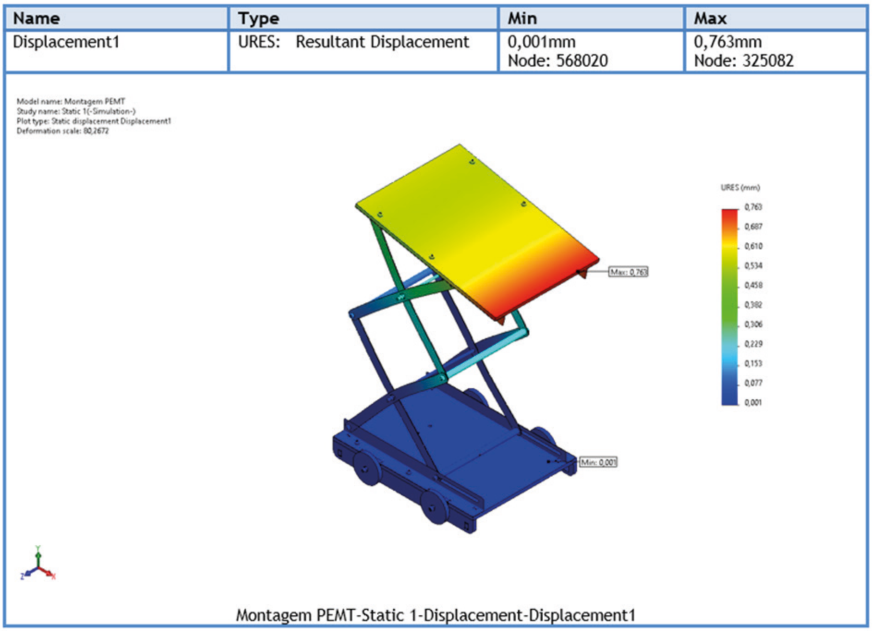


Figure 25 - Resultant displacement plot

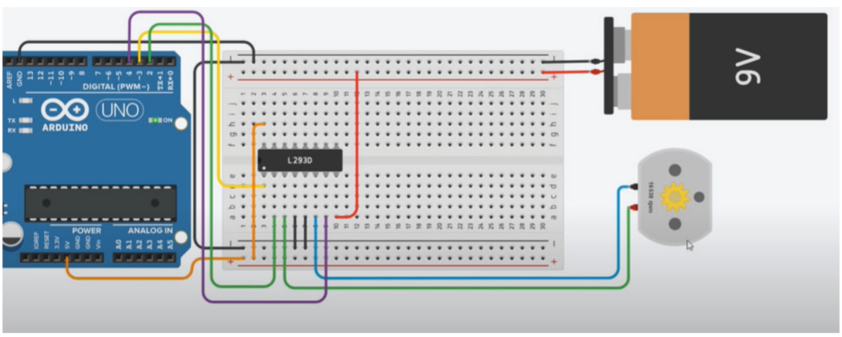


Figure 26 - Circuit assembly diagram for the platform control

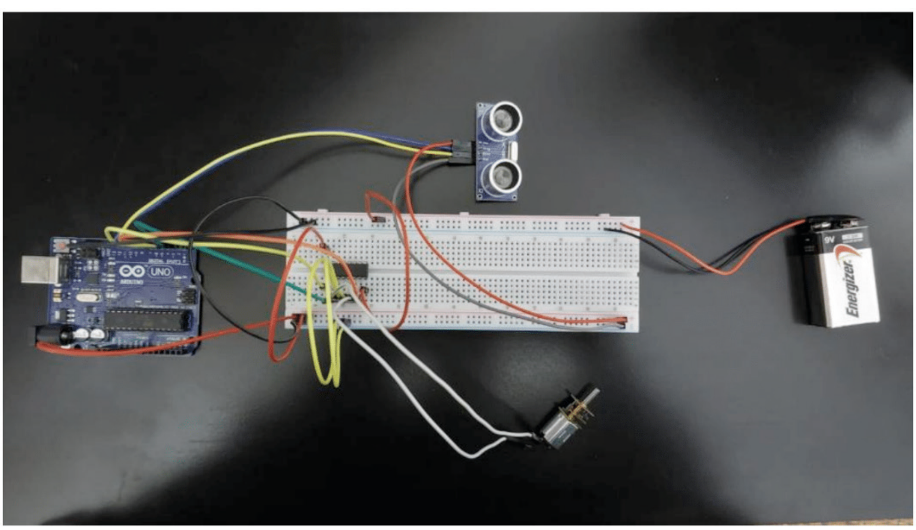


Figure 27 - Electronic circuit used to control the lifting platform

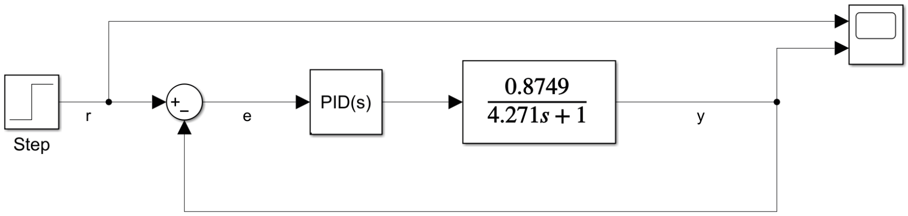


Figure 30 - Control loop of the lift platform using a PID controller

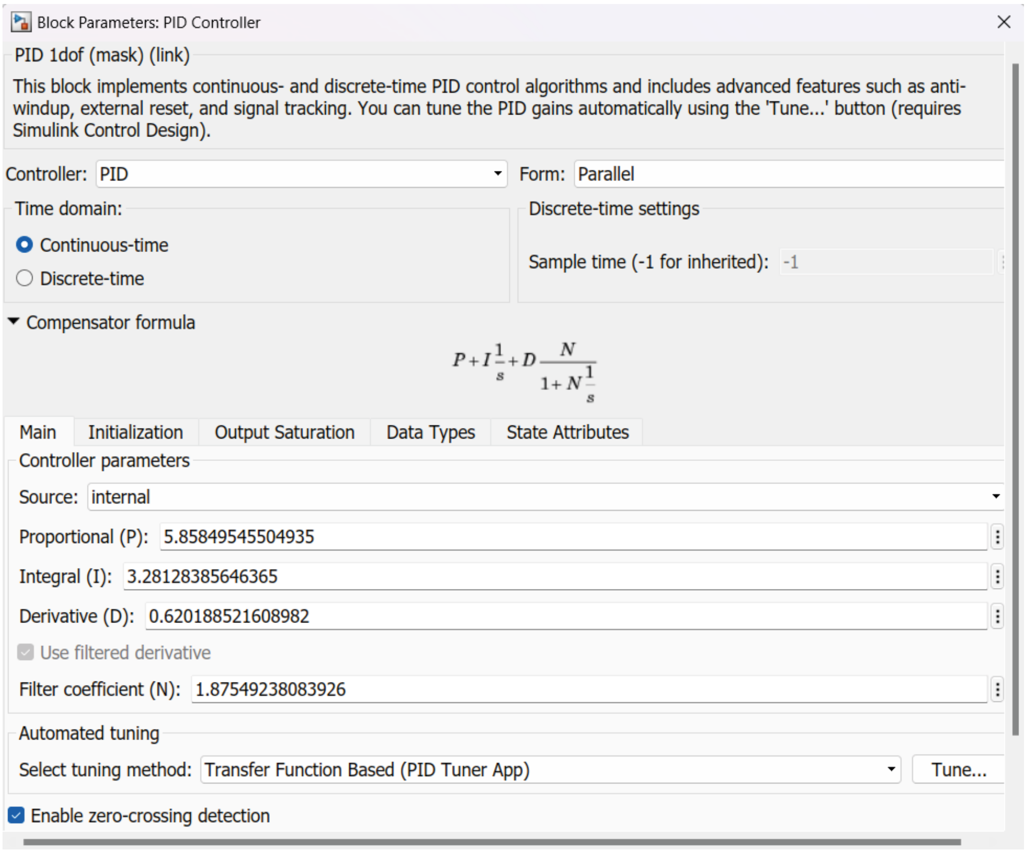


Figure 31 - PID controller gains obtained using the automatic calibration function for minimum response time

first analysis, the group had already defined all the components of the structure with their respective materials as intended for construction, requiring no changes for the purpose of improvement. Thus, the materials used in the second analysis were MDF, aluminum alloys, and aluminum 6063-T6, and all the properties were obtained from the software's material library. Figure 22illustrates the mechanical properties of aluminum 6063-T6 as an example of how material information is presented.

Regarding the load definitions, the group decided to follow the same procedure as in the first analysis, just as they did for the materials, as the desired results still included reactive forces and the structure's load-carrying capacity. Therefore, the upper platform was raised to its maximum height, and a force equivalent to 20 N was applied on its upper surface in a circular region (representing the contact with the bottle). However, with the addition of wheels in the new simplified geometry, the fixation configurations needed to be modified since the group had fixed the entire lower surface of the lower platform to simulate its contact with the ground. Therefore, the regions of the wheels that would be in contact with the ground were defined as fixed, preventing their displacement and rotation. Both conditions can be seen in Figure 23.

The distribution of von Mises stresses throughout the structure is shown in Figure 24.

The von Mises stress is a scalar value that represents a combination of normal and shear stresses in a material. It is commonly used to assess the potential for yielding or failure in ductile materials.

In the plot, different regions of the structure are represented by different colors, indicating the stress levels. Higher stress regions are typically shown in red or warm colors, while lower stress regions are displayed in blue or cool colors.

By examining the von Mises stress distribution, you can assess areas of high stress concentration, potential weak points, or areas that may require further reinforcement or optimization. It helps in understanding the structural behavior under the applied load and provides insights into potential failure mechanisms.

In FEA, the resultant displacement refers to the overall displacement of a structure or a specific point in the structure under the applied loads. It represents the net displacement in terms of magnitude and direction resulting from the applied forces and constraints.

When performing FEA, the structure is divided into finite elements, and each element is analyzed individually. The displacements of these elements are then combined to calculate the overall resultant displacement of the structure.

Resultant displacement provides valuable information about how the structure deforms and moves under the applied loads. It helps engineers understand the behavior and performance of the structure, identify areas of concern, and evaluate whether the displacements meet design requirements or if additional modifications are necessary.

Resultant displacement can be visualized in FEA software through displacement plots, contour plots, or vector plots, where the magnitude and direction of displacement are represented graphically. This allows engineers to analyze and interpret the displacement results to make informed decisions regarding the design and optimization of the structure. The resultant displacement of the lifting platform is shown in Figure 25.

CONTROL SYSTEM OF THE SMALL-SCALE LIFTING PLATFORM MODEL

In this section, the procedure applied for the development of the speed control system for the platform lift will be discussed. As demonstrated, at the beginning of the project, a physical electronic system was planned and designed to capture the platform's information and apply the desired speed control. However, this attempt was not fully successful as the purchased electric motor did not meet the required torque demands. Therefore, the control system was simulated using Matlab and Simulink to fulfill the project's deliverables.

The physical speed control system was developed using an electronic circuit, which included an Arduino UNO board for system programming and implementation of the selected control method, namely PID. The circuit incorporated conventional ultrasonic sensors for sensing and an electric motor without an encoder, chosen based on the theoretical torque calculations required for load lifting. Motor speed variation was achieved using PWM, implemented through an integrated circuit (L293D) containing two H-bridges, of which only one was utilized. The Circuit assembly diagram for the platform control is shown in Figure 26.

The electronic circuit used for controlling the lifting platform control is presented in Figure 27.

The operation of the system relies on the use of an ultrasonic sensor positioned on the fixed base and pointed upwards to capture the position of the movable base of the platform. The distance data between the sensor and the movable base is collected through the analog port of the Arduino UNO board and interpreted within the Arduino code, which is provided in Appendix 1. The difference between the positions at different measurement instants divided by the selected measurement interval in the program indicates the ascent or descent speed of the platform. With this data and knowledge of the desired speed of operation, a PID-style controller, whose gains , and need to be selected by the user for optimal system behavior, checks the error between the actual and desired values and performs the necessary control action to try to minimize the error.

The controller directly affects the PWM signal of the motor, meaning it alters the voltage received by the motor, causing its rotation to increase or decrease automatically according to the command sent by the PID. The controller is also informed of the available operating limits of the mechanical system for performing control. In terms of speed, the PWM value should be between 0 and 255, where 0 indicates the motor is off and 255 indicates the motor is operating at full load, corresponding to the maximum ascent or descent speed. The assembly of the control and sensing systems on the designed lifting platform is depicted in Figure 28.

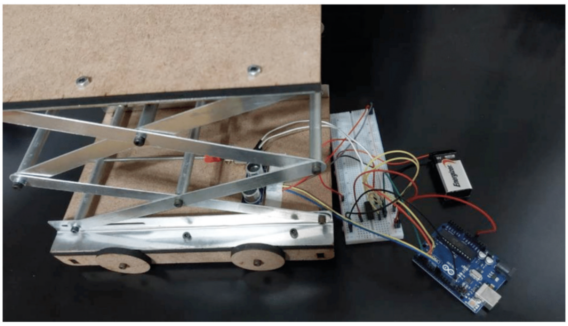


Figure 28 - Assembly of the control and sensing systems on the lifting platform

However, due to excessive friction and clearances identified after assembling the prototype of the mobile work platform lift in this work, the torque indicated by the motor manufacturer was not sufficient to meet the demands of the mechanical system for lifting the platform even without a load. Therefore, to avoid damaging the motor, no further tests were conducted with the PID control system using Arduino as described earlier. Similarly, another electric motor with a higher torque rating was not purchased as the costs would become prohibitively high for the project.

Despite the identified issues with the developed physical control system, a virtual control loop was designed to simulate the same conditions that should be observed with the real system. Simulink was used for this purpose.

The first step in accurately simulating a real system is to obtain the transfer function that characterizes the mechanical assembly. In this case, since the electric motor was available for testing, the transfer function was determined by applying a 5V step signal from the Arduino to drive the electric motor while moving a 1 kg load horizontally.

It is acknowledged that a significant portion of the friction characteristics of the actual platform were lost during this test, but it is deemed acceptable to obtain an approximate transfer function of the designed lifting platform since the acquired electric motor is incapable of lifting the platform. The desired voltage curves and the actual behavior of the motor were extracted from the Arduino and transferred to Simulink, as shown in Figure 29.

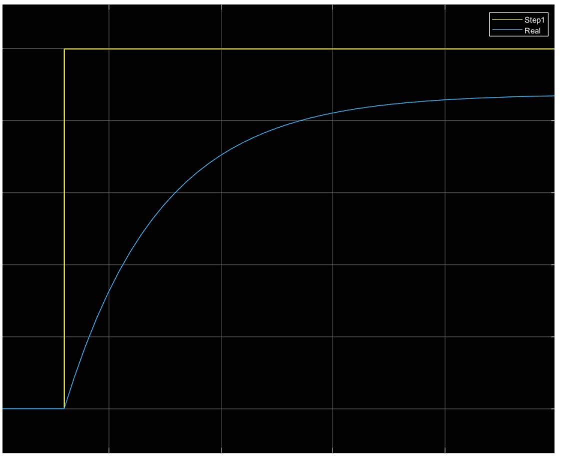


Figure 29 - Comparative graph of the step function and the actual behavior of the motor obtained from the transfer function lifting test

From the obtained actual motor operating curve, using the theory of transient control analysis, the transfer function that characterizes the approximate physical behavior of the lifting platform can be extracted. It is known that the obtained curve is characteristic of a first-order transfer function, which can be expressed as Equation 1, where is the steady-state response of the system to a unit step input and is the time constant, which represents the time required for the response to reach 63% of its steady-state value. By analyzing and for the real curve in Figure 29, the transfer function that approximately represents the designed lifting platform is presented.

$$P(s) = \frac{k_s}{\tau \cdot s + 1} = \frac{0{,}8749}{4{,}271 \cdot s + 1}$$

With the transfer function of the mechanical system in hand, the controller design becomes straightforward using Simulink. The control loop using PID is presented in Figure 30.

In this control loop, state feedback is observed as the input to the PID controller, characterizing a closed-loop system. For the system simulation, a step input (Step block) is introduced, on which the PID controller will act to minimize the error between this input and the response of the transfer function. The block on the rightmost side of the loop is included to visualize the results graphically.

Just like in the Arduino code described earlier, the gains of the PID controller must be designed by the user to achieve the desired behavior in the system. However, the PID block in Simulink has a function to automatically tune the gains of the controller (Tune function), allowing the gains to be found more efficiently and optimized, thereby improving the quality of the controller in the loop. Figure 31 shows the gains obtained with the optimized calibration function in Simulink for achieving the shortest response time of the motor under operating conditions.

Therefore, the simulation with the designed controller was responsible for changing the system's behavior in terms of speed, as illustrated in Figure 32.

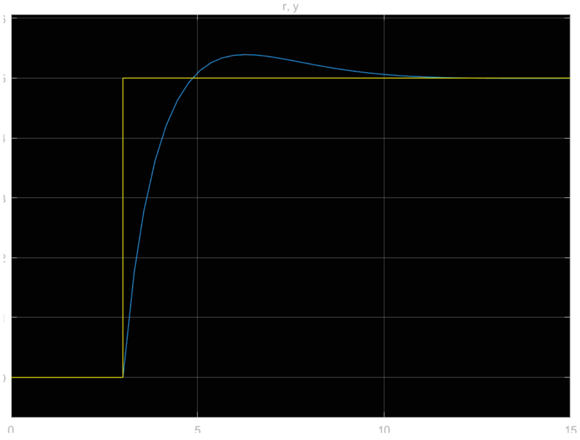


Figure 32 - Simulated final behavior of the system with speed controller

It can be observed, in comparison with the graph in Figure 29, that the inclusion of the PID controller helped the system achieve the desired response in both less time and final value. The overshot obtained in the response can be considered negligible for the expected conditions of use of the platform.

DISCUSSIONS

In this final stage of the project, improvements were made to the initial prototype of the designed mobile work platform to obtain the final prototype of the equipment. With the completed platform, new tests were conducted for both lifting/lowering and sustained load to verify the assembly quality. Both tests were successful, indicating that the implemented improvements indeed optimized the structure, and it can meet the initial project requirements of lifting a load of at least two kilograms. The structural simulations using FEA involved the use of mesh refinement and convergence techniques, and they indicated, like the initial simulations, that the structure is able to support the load specified in the project, which was confirmed by the prototype tests.

Regarding the control system, it was identified that the purchased electric motor for the project was undersized, and thus physical tests could not be conducted. However, the use of the control system simulator in Simulink demonstrated that the PID controller would be crucial in achieving better response in the platform's lifting speed when using the control loop. For future work, it would be necessary to accurately determine the transfer function that describes the system and conduct a physical test with a higher torque electric motor to validate the observations from the simulations.

Although the project was able to achieve all the specified objectives, proposals for future work include increasing the robustness of the trusses used, possibly by increasing the thickness of the material plates to further enhance the stability of the structure and the supported weight. Another proposal is to transform the virtual control system into a physical model capable of controlling the structure.

The results of the design, simulation, production, and testing phases were analyzed and discussed in terms of their technical feasibility. We also reflected on their learning experience, highlighting the challenges and opportunities encountered during the project. The discussions included considerations about potential improvements to the design, manufacturing, and testing processes, as well as the relevance of the project to real-world applications. Overall, the students demonstrated a high level of technical competence, teamwork, and innovation in the development of the mobile work platform lift.

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CONCLUSIONS

This paper provides a comprehensive account of the project, including the design process, the structural analysis methods used to evaluate the safety and performance of the design, the production and assembly processes, and the experimental results of the physical model under predetermined operational conditions. We also reflect on the interdisciplinary approach used in the project and discuss the project outcomes, achievements, and challenges encountered.

The activities of designing, simulating, producing, testing, and evaluating of a small-scale mobile work platform lift were carried out by undergraduate mechanical engineering students in the Integrated Project subject. This subject is designed to challenge students to apply the knowledge and skills acquired in their previous mechanical engineering subjects.

The results of this project demonstrate the effectiveness of project-based learning as an educational approach for teaching mechanical engineering. Through the Integrated Project subject, students were able to develop a range of practical skills, including project management, problem-solving, critical thinking, and communication, all of which are essential for success in the engineering profession.

Overall, the project was successful in achieving its goals, as evidenced by the quality of the final product and the positive feedback from the students. The project also highlights the importance of interdisciplinary collaboration and the integration of different engineering disciplines in the design and development of complex engineering systems.

In conclusion, the project-based learning approach employed in the Integrated Project subject offers a valuable educational opportunity for undergraduate mechanical engineering students. By providing hands-on learning experiences and encouraging interdisciplinary collaboration, this approach can help students develop the practical skills and experience they need to succeed in the engineering profession.

We believe that this project-based learning approach provides an effective way to develop and apply engineering skills in a factual setting, and we hope that our experience will inspire and guide other educators and students in comparable ventures.

ACKNOWLEDGEMENTS

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APPENDIX A

```
#include <HCSR04.h>

//Pinos do sensor ultrassonico
#define TRIGGER   9
```


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```
#define ECHO      8

//Pinos do motor
#define Vmotor       3
#define Horario      2
#define AntiHorario   4
#define tmp   3000

// Inicializa o sensor usando os pinos TRIGGER e ECHO.
UltraSonicDistanceSensor distanceSensor(TRIGGER, ECHO);

//Definicao de variaveis para sensor ultrassonico
float distancia1 = 0;   // Guarda a distancia 1 medida pelo sensor ultrassonico
float distancia2 = 0;   // Guarda a distancia 2 medida pelo sensor ultrassonico
float Vcalc = 0;        // Velocidade calculada da plataforma
int tmpUltra = 500;     // Tempo de amostragem do sensor ultrassonico

// Definicao de variaveis para o motor
const int speedDelay = 1000;
float VelDesejada = 30; // Velocidade de elevacao desejada em mm/s
float PWMmotor = 0;

// Definicao de variaveis para controlador PID
float kp = 0;           // Ganho proporcional
float ki = 0;           // Ganho integral
float kd = 0;           // Ganho derivativo
float erro = 0;
float somaErro = 0;
float ultimoErro = 0;

// Setup inicial do sistema
void setup() {
  pinMode(Vmotor,OUTPUT);
  pinMode(Horario,OUTPUT);
  pinMode(AntiHorario,OUTPUT);

  analogWrite(Vmotor,0);
  digitalWrite(Horario,LOW);
  digitalWrite(AntiHorario,LOW);

  kp = 1;
  ki = 1;
  kd = 1;
```


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```
  Serial.begin(9600);
  delay(2000);
}

// Loop de comandos a serem realizados no circuito
void loop(){

  // Calculo da velocidade com o sensor ultrassonico
  distancia1 = distanceSensor.measureDistanceCm();
  delay(tmpUltra);
  distancia2 = distanceSensor.measureDistanceCm();
  Vcalc = (distancia2 - distancia1)*10/(tmpUltra*0.001);

  // Controle de velocidade do motor
  // Aplicacao do controlador PID em malha fechada
  erro = VelDesejada - Vcalc;
  somaErro = somaErro + erro;

  PWMmotor = (kp*erro) + (ki*somaErro) * (kd*(erro-ultimoErro));

  ultimoErro = erro;

  if(PWMmotor > 255) PWMmotor = 255; // Velocidade maxima, acima dela o motor pode queimar
  if(PWMmotor < 70) PWMmotor = 0; // Velocidade minima, abaixo dela o motor desliga

  if(erro < 0){
    digitalWrite(Horario,HIGH);
    digitalWrite(AntiHorario,LOW);}

    else{
    digitalWrite(Horario,LOW);
    digitalWrite(AntiHorario,HIGH);}

  analogWrite(Vmotor,PWMmotor);

  //Exibir valores
  Serial.print(Vcalc); Serial.println(" mm/s");
  Serial.print("Erro: "); Serial.println(erro);
  Serial.print("PWM do motor: "); Serial.println(PWMmotor);
```