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ENGINEERING THE ALIGNMENT OF OPEN-WHEEL RACECARS: A METHODOLOGICAL FRAMEWORK FOR PRODUCT DESIGN IN PROJECT-BASED LEARNING

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Abstract. *This work presents the development of a low-cost alignment apparatus specifically designed for open-wheel student racing vehicles, within the scope of an engineering design methodology course. The project originated from the identification of practical challenges faced by teams participating in Baja SAE and Formula SAE competitions, particularly the need to reduce setup time and improve alignment accuracy. The design process was structured through a comprehensive feasibility study, encompassing market research, functional specifications, creative synthesis of alternatives, and multi-criteria decision-making using the Analytic Hierarchy Process (AHP). The selected solution integrates standardized components, laser-based measurement systems, and ergonomic features, balancing precision, usability, and manufacturability. Prototyping activities involved iterative development, testing, and optimization of mechanical, structural, and electronic subsystems. The final prototype demonstrated technical feasibility and potential for implementation in real-world applications by student teams. This study highlights the effectiveness of Project-Based Learning (PBL) strategies in fostering technical skills, decision-making abilities, and practical problem-solving in engineering education.*

Keywords*: Engineering Design, Product Development, Project-Based Learning, Wheel Alignment Device, Open-Wheel Racecars*

Resumo. *Este trabalho apresenta o desenvolvimento de um aparato de baixo custo para alinhamento de veículos do tipo open-wheel, voltados a competições estudantis como Baja SAE e Fórmula SAE. O projeto foi desenvolvido no contexto de uma disciplina de metodologia de projeto, com base na identificação de desafios enfrentados pelas equipes, especialmente a necessidade de redução do tempo de setup e o aumento da precisão nas medições. O processo de desenvolvimento envolveu um estudo de viabilidade detalhado, incluindo análise de mercado, definição de especificações funcionais, geração criativa de alternativas e tomada de decisão por múltiplos critérios, utilizando o método Analytic Hierarchy Process (AHP). A solução escolhida integrou componentes padronizados, sistemas de medição baseados em laser e elementos ergonômicos, conciliando precisão, facilidade de uso e viabilidade de fabricação. As atividades de prototipagem envolveram desenvolvimento iterativo, testes e otimizações dos subsistemas mecânicos, estruturais e eletrônicos. O protótipo final demonstrou viabilidade técnica e potencial de aplicação prática pelas equipes estudantis. Este estudo evidencia a eficácia das estratégias de aprendizagem baseada em projetos, em inglês Project-Based Learning (PBL), no desenvolvimento de competências técnicas, capacidade de decisão e solução prática de problemas na formação em engenharia.*

Palavras chave: *Metodologia de Projeto, Desenvolvimento de Produto, Aprendizagem Baseada em Projetos, Aparato de Alinhamento, Veículos Open-Wheel*

1. INTRODUCTION

Project-Based Learning (PBL) has emerged as a transformative pedagogical approach in engineering education, emphasizing the application of theoretical knowledge to real-world problems (RIO & RODRIGUEZ, 2022). By engaging students in complex, open-ended projects, PBL fosters critical thinking, collaboration, and practical skills essential for engineering practice (KUPPUSWAMY & MHAKURE, 2020). This educational model aligns with the demands of modern engineering curricula, which aim to produce graduates capable of addressing multifaceted challenges through innovative solutions (SHARMA *et al.*, 2020).

In the context of automotive engineering, particularly within student-led racing teams such as Baja SAE and Formula SAE, precise wheel alignment is crucial for vehicle performance and safety (REDDY & MAHATO, 2021; CHEPKASOV *et al.*, 2016). Traditional alignment methods often lack portability and adaptability, posing challenges for teams operating in dynamic environments (XU *et al.*, 2022). The development of a low-cost, portable alignment apparatus addresses these limitations, providing a practical solution that enhances the educational experience by integrating design, analysis, and prototyping skills (SABZEVARI *et al.*, 2025).

This study presents the design and development of an alignment device tailored for open-wheel student racing vehicles, undertaken as a capstone project in an engineering design methodology course. The project followed a structured design process, beginning with a comprehensive feasibility study that included market analysis, functional requirements specification, and the generation of design alternatives (ASIMOW, 1962). A multi-criteria decision-making approach, specifically the Analytic Hierarchy Process (AHP), was employed to evaluate and select the optimal design solution (POTOMKIN *et al.*, 2024). Subsequent stages involved detailed design, prototyping, and testing to validate the device's performance and usability (KAMINSKI, 2000; LESKO, 2011).

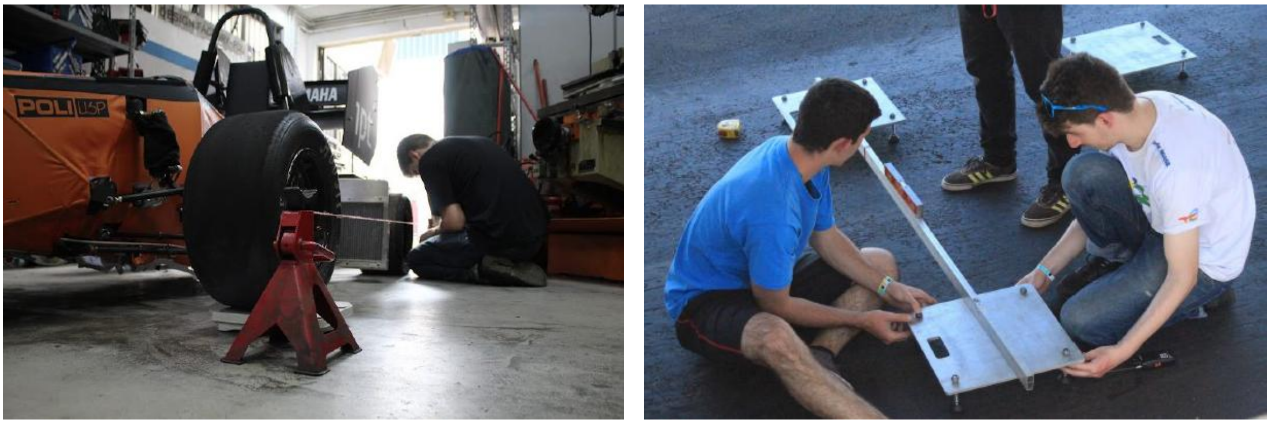
The implementation of this project within a PBL framework not only resulted in a functional engineering solution but also provided students with experiential learning opportunities that mirror professional engineering practice (LUBURIć *et al.*, 2024). By navigating the complexities of product development, from conceptualization to realization, students gained insights into the iterative nature of design, the importance of interdisciplinary collaboration, and the application of analytical tools in decision-making processes (DIETER & SCHMIDT, 2013).

2. METHODOLOGY

The development of the alignment apparatus was guided by a structured Engineering Design Methodology, divided into five main stages: (i) identification of needs, (ii) market analysis, (iii) definition of functional and constructive specifications, (iv) generation and filtering of design alternatives, and (v) financial feasibility analysis.

2.1. Identification of needs

The project was initiated with an in-depth study of the alignment procedures adopted by Baja SAE and Formula SAE student teams. Two main critical aspects were identified: the excessive time required to perform setup adjustments and the lack of precision inherent to the current procedures, which are predominantly visual and manual. Figure 1 illustrates the typical alignment procedure currently used by student teams, highlighting the difficulties associated with visual inspection and the need for multiple iterative adjustments.



a) Procedure for adjusting the toe angle by modifying the length of the steering rods

b) Procedure for leveling the ground surface prior to camber angle measurement

Figure 1. Conventional alignment procedure adopted by student teams

2.2. Market analysis

A comprehensive market research was conducted to define the target audience, analyze existing products, and understand the competitive landscape. The analysis indicated that while some professional alignment tools exist, their high cost makes them inaccessible to student teams. Table 1 summarizes the main characteristics of the identified competitors.

Table 1. Comparative analysis of wheel alignment devices available in the market

Device	Sniper V2 Inox Aligner	Camber Gauge	Three-Angle Gauge
Price	BRL 2,990.00	BRL 187.67	BRL 763.81
Angles Measured	Camber and Toe	Camber	Caster, Kingpin, Camber
Mechanism	Laser	Bubble Level	Bubble Level
Accuracy	0.50°	0.50°	0.25°
Dimensions (mm)	150 x 50 x 55	135 x 55 x 55	220 x 85 x 85
Mass	0.9 kg	0.3 kg	1.5 kg

2.2. Definition of product specifications

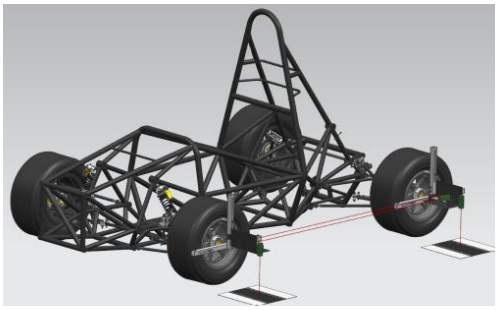
Based on the identified needs and market conditions, the main functional and constructive specifications of the apparatus were defined. These include a maximum measurement uncertainty of 0.5°, adaptability to different wheel sizes, maximum dimensions compatible with the space constraints of student teams' work areas, and a target retail price of BRL 300. The device must allow reducing the alignment time to 1 h. Table 2 presents the consolidated product specifications.

Table 2. Functional and constructive specifications of the alignment apparatus

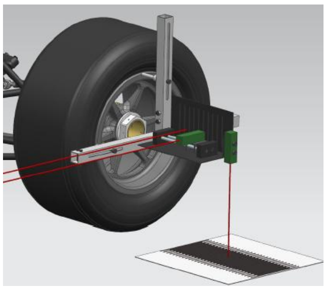
Specification	Value
Maximum selling price	BRL 300.00
Annual production	1800 units
Maximum measurement uncertainty	0.50°
Adaptability to different wheel sizes	10" to 16" rims
Measurement indicator	Character height ≥ 10 mm
Maximum dimensions	370 mm x 590 mm
Product lifetime	2 years
Mass	2 kg
Minimum resistance classes	IP 67, IK 10

2.4. Generation and filtering of design alternatives

Employing creative development methods, such as brainstorming and morphological analysis, the product was divided into four subsystems: (i) vehicle attachment mechanism, (ii) toe measurement mechanism, (iii) camber measurement mechanism, and (iv) main structure material. A total of 735 possible configurations were generated through combinations of different alternatives. This initial set was subsequently filtered through physical feasibility analysis, economic constraints, and performance criteria. The process resulted in a reduced set of 24 viable alternatives (ARIK & TOPÇU, 2023). Figure 2 shows an example of one of the evaluated design alternatives.



a) Mechanical attachment



b) Laser measurement detail

Figure 2. Example of evaluated design alternative combining laser measurement and mechanical attachment

2.5. Financial feasibility analysis and final solution selection

The selection of the most suitable solution was supported by the definition of evaluation criteria, initially proposed through a brainstorming session conducted by the design team. A total of thirteen criteria were identified, encompassing technical, economic, and operational aspects. However, a detailed analysis was subsequently carried out to identify interdependencies among them and to merge overlapping concepts.

As a result, six key criteria were selected for the decision-making process:

1. Use of standardized components: this criterion indirectly reflects aspects related to cost reduction, manufacturing feasibility, and lead time minimization.
2. Ease and speed of use: this consolidated criterion merges considerations related to assembly/disassembly, operational simplicity, and the learning curve required for users.
3. Ease of transportation: given the operational context of student competitions, high portability was considered essential for field usability.
4. Manufacturing cost: this parameter directly impacts market competitiveness and product adoption potential.
5. Performance: a comprehensive criterion encompassing reliability, accuracy, and overall technical capability of the device.
6. User preference: reflects the potential acceptance of the product by the target audience, ensuring alignment with user expectations and needs.

A multi-criteria decision-making approach was adopted to evaluate the filtered alternatives, considering factors such as cost, complexity of manufacturing, and ease of use. AHP was employed to support the selection of the optimal solution, aligning technical feasibility with market expectations (DONG *et al.*, 2023; SAATY, 1980). Table 3 presents the final ranking of the evaluated solutions based on financial feasibility criteria.

Table 3. Ranking of design alternatives after financial feasibility analysis

Solution ranking	Solution code	Components	Justification for ranking
1st	23	Clamps, string, bubble level, plastic	The simplest solution, as it relies solely on clamps and basic supports for the level and the string, requiring no additional components.
2nd	22	Clamps, string, laser, plastic	A solution that remains simple, but requires an additional metal plate for camber measurement, introducing slightly greater complexity compared to solution 23.
3rd	20	Clamps, laser, bubble level, plastic	More complex than the previous alternatives due to the integration of a measurement mechanism directly attached to the clamps, eliminating isolation as in solution 22.
4th	14	Clamps, turntable, bubble level, plastic	Similar to solution 20, but incorporating a turntable system, which increases complexity since it involves both a base and a rotating component.
5th	19	Clamps, laser, bubble level, plastic	The first alternative that requires the use of protective plates both on the clamps and on the ground surface, resulting in higher assembly complexity.
6th	13	Clamps, turntable, laser, plastic	The most complex alternative due to the combined use of a turntable and a laser system, making it considerably more elaborate than solution 14.

3. RESULTS

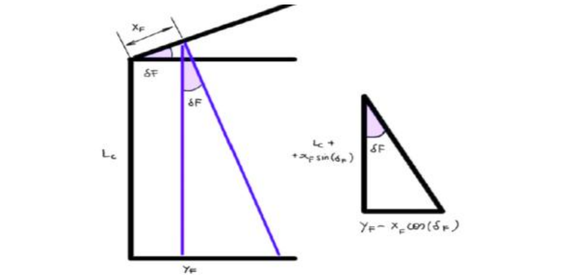
An optimization analysis was conducted to develop a standardized procedure for adjusting camber and toe angles, aiming to minimize setup time and ensure repeatability during alignment operations. The proposed method is supported by a measurement guide and a dedicated software tool, designed to process user inputs and provide real-time feedback on the current alignment conditions, facilitating precise adjustments.

Given that the measured toe angles are typically small, mathematical modeling was based on Taylor Series approximations, enabling the estimation of associated errors for angles up to 5°, which corresponds to the maximum adjustment range commonly required by the target market, as indicated in Tab. 4.

Table 4. Estimated errors resulting from Taylor Series approximations for toe angles up to 5°

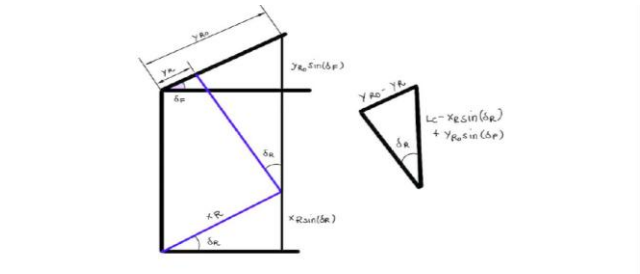
Mathematical approximation	**Associated error for θ = 5°**
$\sin(\theta) = \theta$	$1.1x10^{-4}$
$\cos(\theta) = 1$	$3.8x10^{-3}$

The error analysis demonstrated that the deviations introduced by these mathematical approximations were negligible when compared to other uncertainty sources, such as the laser projection diameter on the measurement plane or potential manufacturing misalignments between the laser and its housing. A similar modeling approach was applied to define the adjustment method for the rear wheels, following the schematic representation shown in Fig. 3, and adopting the same mathematical assumptions as in the front wheel case (GILLESPIE, 2021).



$$tg(\delta_F) = \left(\frac{y_F - x_F.cos(\delta_F)}{L_c + x_F.sen(\delta_F)}\right) \Rightarrow sen(\delta_F)[L_c + x_F.sen(\delta_F)] = y_F.cos(\delta_F) - x_F.cos^2(\delta_F)$$

a) Front wheel toe angle

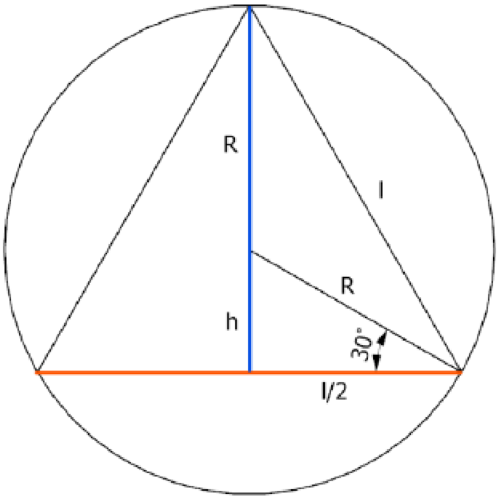


$$sen(\delta_R) = \frac{y_{R_0} - y_R}{L_C - x_R.sen(\delta_R) + y_{R_0}sen(\delta_F)} \Rightarrow \delta_R = \frac{(L_C + y_{R_0}\delta_F) + \sqrt{(L_C + y_{R_0}\delta_F)^2 - 4.x_R(y_{R_0} - y_R)}}{2.x_R}$$

b) Rear wheel toe angle

Figure 3. Schematic representation of the toe angle measurement method

Based on the product specifications, the alignment device was required to accommodate wheels with diameters ranging from 10" to 16". To ensure this versatility, calculations were performed to define the minimum and maximum extension limits of the clamping mechanism, as illustrated in Fig. 4.



$$cos(30°) = \frac{\sqrt{3}}{2} = \frac{l/2}{R} \Rightarrow l = R\sqrt{3}$$

$$sen(30°) = \frac{1}{2} = \frac{h}{R} \Rightarrow h = \frac{R}{2} \Rightarrow H = \frac{3R}{2}$$

Figure 4. Dimensional analysis for determining the adjustment range of the clamping mechanism

Considering the smallest and largest radii (R) of 127.0 mm and 203.2 mm, respectively, an additional safety margin of 20 mm was incorporated. This margin aimed to guarantee proper adaptability even in cases of deformed or damaged wheels. Furthermore, an extra 15 mm was added to the upper limit to account for the remaining material beyond the end of the slot, ensuring the structural integrity of the component after machining.

A key aspect of the product development was the definition of appropriate geometry for the laser housing and the optimal internal arrangement of its components. An optimization analysis was conducted using CAD modeling to minimize material usage while maximizing the internal space efficiency, ensuring compactness without compromising assembly feasibility.

Following the initial virtual modeling, a physical prototype of the housing and its cover was produced using rapid prototyping techniques, specifically 3D printing with PLA material. The electrical components and the laser module were assembled to validate both the internal geometry and the ease of assembly. During the first assembly attempt, interference was observed between the laser and the housing cover, preventing proper closure. Material removal using milling operations was required to eliminate this interference and enable correct assembly. Once assembled, the prototype validated the available internal space for accommodating the electrical system and the laser.

Additionally, the assembly process revealed that routing the wiring between the battery compartments was challenging due to insufficient space. To address this issue, the diameter of the cable passage was increased from 2 mm to 4 mm, and the height of the housing structure was increased from 15 mm to 17 mm, as shown in Fig. 5. The cover geometry remained unchanged to preserve the effectiveness of the sealing interface, essential for ensuring water resistance.

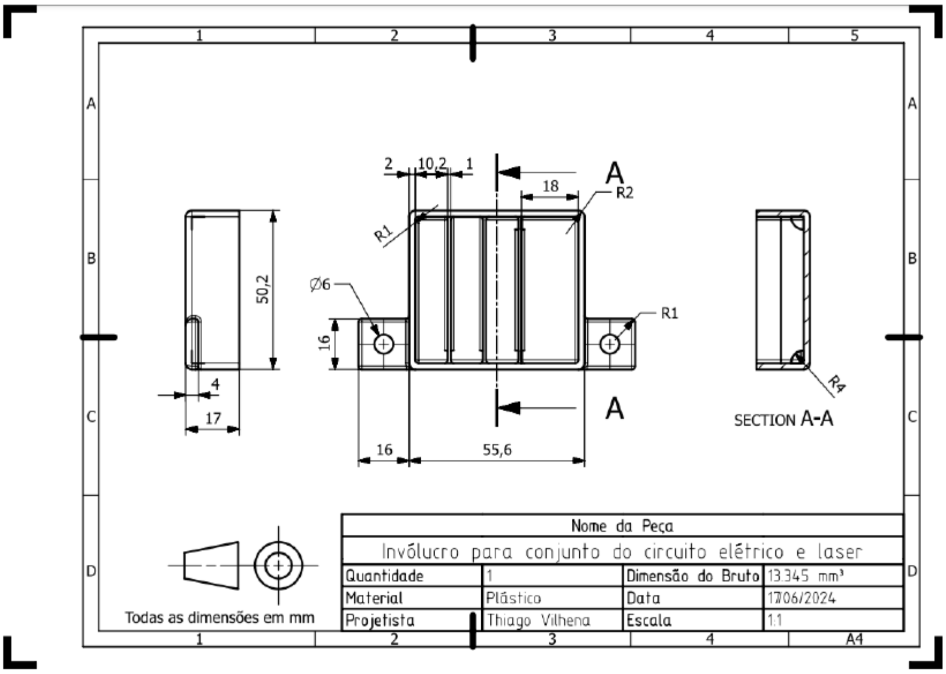


Figure 5. Geometry of the laser housing after design modification

A physical prototype was developed with the objective of testing and validating the design analyses, leading to minor design adjustments based on the observed results. During the assembly of the electrical circuit, a conventional push-button was used instead of a switch-type button due to its easier availability. This substitution did not affect the testing procedures, since the button could simply remain pressed during operation. Regarding the manufacturing of the clamping jaws, adaptations were necessary due to equipment limitations. The jaws were fabricated specifically for 10" wheels from the Equipe Poli Racing (EPR), as the group did not have access to appropriate milling equipment required to machine the slots. Consequently, the fixation system adopted through-holes with bolts welded in place, as full-threaded M6 bolts were unavailable, preventing conventional nut fastening.

Additionally, the lateral adjustment slot of the laser guide was not manufactured. Instead, two fixed holes were drilled, allowing only a single lateral position configuration for the laser. Initial testing of the electrical system confirmed its correct operation. However, during clamping tests, the jaws exhibited slippage when in contact solely with the bolt heads. To mitigate this, rubber hoses were installed on the ends of the bolts, increasing surface friction and allowing better adaptability through controlled deformation. An optical test was also conducted to evaluate the laser visibility on different background colors as shown in Fig. 6.

a) Laser projection on a dark background b) Laser projection on a light background

Figure 6. Laser projection tests on different backgrounds

The results indicated superior readability on dark surfaces, leading to the decision to adopt a dark-colored measurement plane in the final design. Additional tests were performed to verify the laser power and to validate the compatibility between the housing geometry and the internal electrical components, confirming proper accommodation and functionality.

Following the analyses, prototyping stages, and validation tests, the final design of the alignment device was established. The complete CAD assembly of the final product is presented in Fig. 7, illustrating all the integrated subsystems.

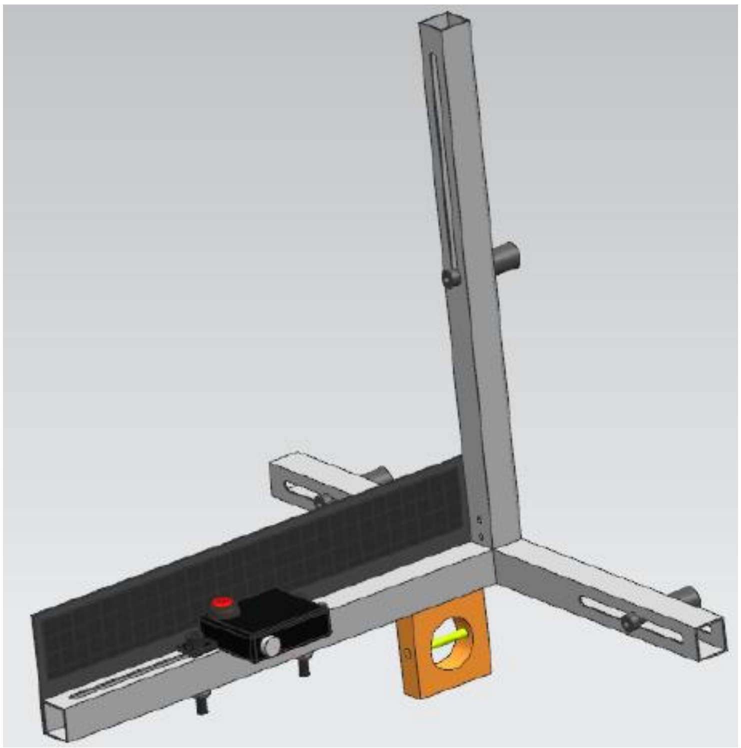


Figure 7. Final CAD model of the alignment device

A detailed technical drawing of the complete assembly is shown in Fig. 8.

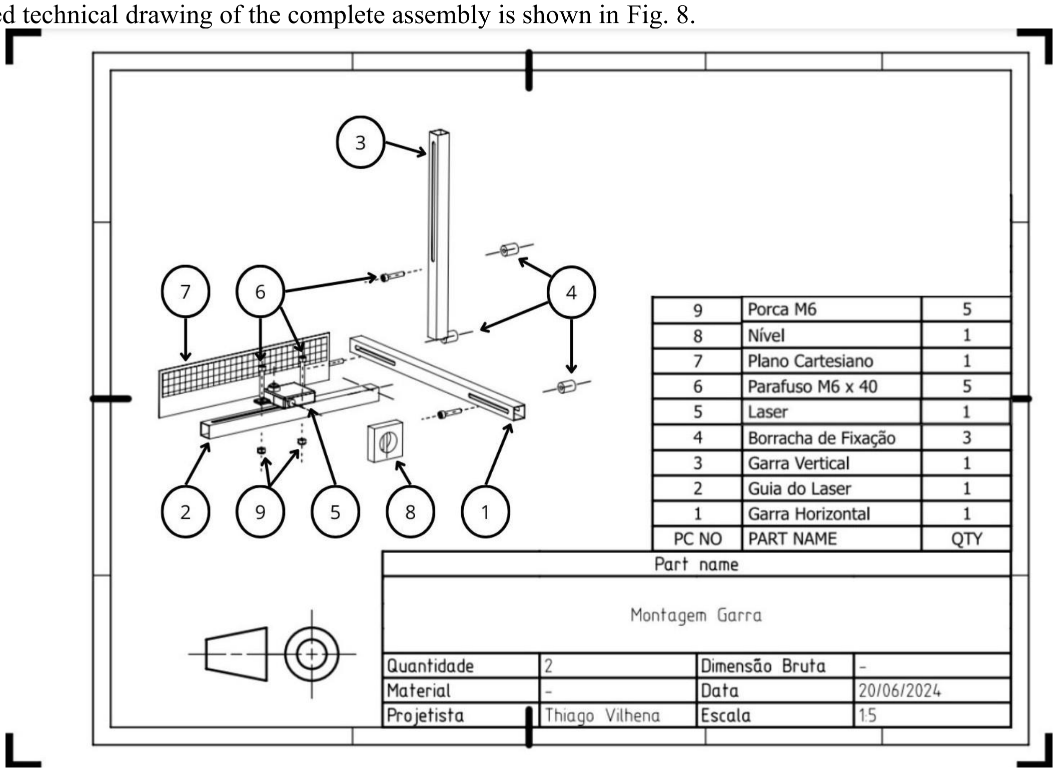


Figure 8. Final CAD model of the alignment device

Figure 9 shows the final prototype, including the addition of a spirit level to assist the alignment procedure.

Figure 9. Final CAD model of the alignment device

Finally, Table 5 presents a summary of the main results obtained from the prototype testing, listing both the validated functionalities and the components that were modified or incorporated into the final design.

Table 5. Main results obtained from prototype testing, including validated functionalities and design modifications

Component	Outcome
Laser	Validation of the selected power output
Clamping jaws	Modification of the fixation system by adding rubber elements to improve grip and adaptability
Electrical circuit	Functional validation through experimental testing
Housing	Geometric modifications to address assembly difficulties and component interference
Measurement Plane	Selection of a dark surface color to improve laser visibility and reading accuracy

4. CONCLUSIONS

This work presented the development of a wheel alignment device specifically designed for open-wheel student racing vehicles, integrating engineering design methodology within a project-based learning environment.

The proposed solution met all functional, constructive, and economic requirements established during the feasibility study. The structured design process, supported by multi-criteria decision-making techniques, enabled the selection and refinement of an optimized solution capable of reducing alignment time, improving accuracy, and enhancing usability in competitive environments.

Prototyping and experimental validation confirmed the technical feasibility of the device and allowed for targeted design improvements, particularly in the housing of the laser system. The project demonstrated the effectiveness of project-based learning strategies in fostering technical competencies, problem-solving skills, and practical engineering experience among students.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY FOR THE INFORMATION

The authors bear full responsibility for the accuracy and integrity of the information presented in this work.