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Innovative Automated Manual Transmission (AMT) System for Bicycles: Design, Implementation and Control

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Anahtar Kelimeler

Otomatikleştirilmiş Manuel Şanzıman (AMT)
Manuel Şanzıman Sistemi
Akıllı Vites Değiştirme
Çoklu Sürüş Modu
Bisiklet

Graphical/Tabular Abstract (Grafik Özet)

In this study, an AMT system that automates manual gear shifting on bicycles has been developed, high accuracy performance has been achieved by determining and implementing gear changes with sensor data, and the system's user-friendly and low-cost design has been successfully tested. / Bu çalışmada bisikletlerde manuel vites değişimini otomatik hale getiren bir AMT sistemi geliştirilmiş, vites değişimlerinin sensör verileriyle belirlenip uygulanmasıyla yüksek doğruluk performansı elde edilmiş, sistemin kullanıcı dostu ve düşük maliyetli tasarımı başarıyla test edilmiştir.

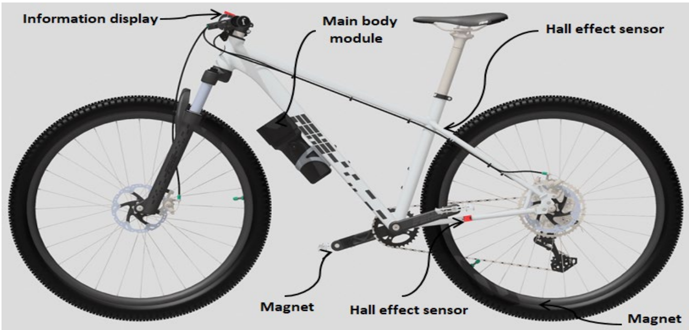

***Figure A**: Proposed AMT system /**Şekil A:** Önerilen AMT Sistemi*

Highlights (Önemli noktalar)

- *Implementation of Automated Manual Transmission (AMT) systems to bicycles / Otomatikleştirilmiş Manuel Şanzıman (AMT) sisteminin bisikletlerde uygulanabilirliği*
- *Automating manual gear shifts with an intelligence-based system / Zekâ tabanlı sistemle manuel vites değişimlerinin otomatikleştirilmesi*
- *High-accuracy gear shifts using sensor data / Sensör verileri ile yüksek doğrulukta vites geçişlerinin gerçekleştirilmesi*

Aim (Amaç): *This study aims to develop an innovative Automated Manual Transmission (AMT) system that automates manual gear shifting on bicycles. / Bu çalışma, bisikletlerde manuel vites değişimini otomatik hale getiren yenilikçi bir Otomatikleştirilmiş Manuel Şanzıman (AMT) sistemi geliştirmeyi amaçlamaktadır.*

Originality (Özgünlük): *This study presents a unique algorithm for achieving seamless and efficient gear shifts, a mechatronic system design adaptable to different types of bicycles, and multiple driving modes (eco, normal, sport) to optimize driving performance and comfort. / Bu çalışma, kesintisiz ve verimli vites geçişleri elde etmek için benzersiz bir algoritma, farklı bisiklet türlerine uyarlanabilen bir mekatronik sistem tasarımı ve sürüş performansını ve konforunu optimize etmek için çoklu sürüş modları (eko, normal, spor) sunmaktadır.*

Results (Bulgular): *The findings confirmed the reliability of the developed AMT system, demonstrating its ability to process sensor data, execute gear shifts accurately under various driving conditions, and deliver real-time information to the user. / Bulgular, geliştirilen AMT sisteminin güvenilirliğini doğrulamış, sensör verilerini işleme, çeşitli sürüş koşullarında vites değiştirme işlemlerini doğru bir şekilde gerçekleştirme ve kullanıcıya gerçek zamanlı bilgi sunma yeteneğini göstermiştir.*

Conclusion (Sonuç): *This study successfully developed and validated an intelligent AMT system for bicycles, proving its reliability and accuracy in automating manual gear shifts through sensor-driven data and extensive testing. / Bu çalışma, sensör odaklı veriler ve kapsamlı testler yoluyla manuel vites değiştirmeyi otomatikleştirmedeki güvenilirliğini ve doğruluğunu kanıtlayarak bisikletler için akıllı bir AMT sistemini başarıyla geliştirmiş ve doğrulamıştır.*

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Abstract

In recent years, the bicycle industry has experienced remarkable advancements through the incorporation of innovative technologies and transformative design principles. In this context, the Automated Manual Transmission (AMT) system, widely adopted in the automotive sector, represents a critical technological milestone. These systems have offered many advantages, such as increased fuel efficiency, reduced operating costs, and increased user comfort in motor vehicles by automating traditional manual transmissions through advanced electronic components and actuators, and have thus gained wide acceptance in the sector. Despite this proven success in the automotive industry, the applicability of a similar system in bicycles remains an under-researched area, which constitutes a significant gap in the development of technological innovations in the bicycle industry. This study presents the development of an innovative gear-shifting system that automates the traditional manual gear-shifting process on bicycles with an intelligence-based system. The system, which autonomously determines optimal gear shifts by processing data obtained from sensors and implements these decisions with an integrated actuator mechanism, enables manual transmission bicycles to be practically converted to automatic transmission. Notable for its compact design, low cost, and user-friendly assembly, this system also optimizes performance and comfort by offering multiple riding modes that dynamically adapt to user preferences or changing riding conditions. The developed system has been integrated into a manual transmission bicycle and thoroughly tested, with its ability to perform automatic gear shifts with high accuracy scientifically proven.

Manuel Bisikletler için Yenilikçi Otomatikleştirilmiş Manuel Şanzıman (AMT) Sistemi: Tasarım, Uygulama ve Kontrol

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Öz

Son yıllarda bisiklet endüstrisi, yenilikçi teknolojilerin ve dönüştürücü tasarım ilkelerinin bir araya getirilmesiyle kayda değer ilerlemeler kaydetmiştir. Bu bağlamda, otomotiv sektöründe yaygın olarak kullanılan Otomatikleştirilmiş Manuel Şanzıman (AMT) sistemi, önemli bir teknolojik dönüm noktasını temsil etmektedir. Bu sistemler, gelişmiş elektronik bileşenler ve eyleyiciler aracılığıyla geleneksel manuel şanzımanların otomatikleştirilmesiyle motorlu taşıtlarda yakıt verimliliğinin artması, işletme maliyetlerinin azalması, kullanıcı konforunun artması gibi pek çok avantaj sunmuş ve sektörde geniş kabul görmüştür. Otomotiv sektöründeki bu kanıtlanmış başarıya rağmen, benzer bir sistemin bisikletlerde uygulanabilirliği yeterince incelenmemiş bir alan olarak kalmakta ve bu durum, bisiklet endüstrisinde teknolojik yeniliklerin geliştirilmesi açısından önemli bir eksiklik oluşturmaktadır. Bu çalışma, bisikletlerde geleneksel yöntemlerle manuel şekilde gerçekleştirilen vites değiştirme sürecini, zekâ tabanlı bir sistemle otomatikleştiren yenilikçi bir vites değiştirme sisteminin geliştirilmesini sunmaktadır. Sensörlerden elde edilen verileri işleyerek optimal vites geçişlerini otonom bir şekilde belirleyen ve bu kararları entegre bir eyleyici mekanizmasıyla uygulayan sistem, manuel şanzımanlı bisikletlerin pratik bir şekilde otomatik vitese dönüştürülmesini sağlamaktadır. Kompakt tasarımı, düşük maliyeti ve kullanıcı dostu montajıyla dikkat çeken bu sistem, aynı zamanda kullanıcı tercihlerine veya değişen sürüş koşullarına dinamik olarak uyum sağlayan birden fazla sürüş modu sunarak performansı ve konforu da optimize etmektedir. Geliştirilen sistem, manuel şanzımanlı bir bisiklete entegre edilmiş ve kapsamlı bir şekilde test edilmiş olup, otomatik vites geçişlerini yüksek doğrulukla gerçekleştirebildiği bilimsel olarak kanıtlanmıştır.

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1. INTRODUCTION (GİRİŞ)

Bicycles offer profound advantages, including enhancing cardiovascular and musculoskeletal health, reducing environmental impact through sustainable transportation, and serving as an economically viable alternative to motorized vehicles [1-3]. Furthermore, bicycles offer a cost-effective mode of transportation compared to motorized vehicles, requiring less maintenance and no fuel costs, which makes them an attractive option for individuals seeking affordable mobility solutions. Their versatility allows them to be used for various purposes, ranging from urban commuting to recreational activities, making them a cornerstone in addressing environmental challenges and promoting public health initiatives [4]. However, despite these numerous benefits, traditional bicycles with manual gear-shifting mechanisms present significant challenges. Drivers are often required to adjust gears frequently to adapt to varying terrains, which can disrupt the riding experience. These frequent gear shifts demand not only physical effort but also a high level of mental focus, which can lead to diminished performance and increased fatigue, particularly during long rides or intense cycling sessions. Moreover, such frequent shifting can be impractical in fast-paced urban environments or during recreational activities, where ease of use and seamless transitions are paramount for maintaining optimal cycling efficiency and driver comfort. While ensuring optimal gear efficiency and comfort is essential, it is equally important to define these concepts accurately. The human body expends energy during any physical activity, triggering various physiological response mechanisms. Studies have shown that an increase in heart rate induces physiological effects such as perspiration, alterations in blood flow velocity, and temperature fluctuations, which may be perceived as discomforting factors [5]. These effects can be considered as elements that can negatively affect comfort during riding. In this context, a comfortable cycling experience is inherently linked to minimizing physical exertion and mitigating these physiological responses. The most effective way to achieve this goal is to optimize gear change processes in a way that requires the user to spend the minimum effort. To address these limitations, integrating Automated Manual Transmission (AMT) systems into bicycles presents a promising solution that can significantly enhance the cycling experience [6-11].

AMT systems, which seamlessly integrate the precision of manual transmissions with the convenience of automatic systems, achieve gear shifts through advanced electronic controllers and actuator mechanisms [12-14]. When these systems are implemented on bicycles, they eliminate frequent manual adjustments, enhancing convenience, efficiency, and comfort. They ensure smooth gear transitions and reduce driver fatigue by utilizing real-time data from sensors capable of measuring parameters such as terrain slope, wheel speed, and pedal cadence [15-17]. In addition to environmental parameters such as terrain slope, wheel speed, and pedal cadence, recent studies have explored integrating user-specific physiological data into the gear-shifting process. These systems are designed to adapt not only to external conditions but also to the driver's physiological state, such as heart rate, body temperature, and even metabolic rate. By incorporating sensors that track these variables, the system can respond to the driver's fatigue level, improving overall performance and ensuring a more personalized cycling experience. For example, some studies have proposed gear-shifting systems that adapt based on heart rate variations, adjusting the gear ratio to optimize the driver's effort during increased physical exertion [18,19]. This not only improves the ride's efficiency but also ensures that the driver's body is not overly strained, thus enhancing comfort and performance throughout the cycling session.

In this study, a sensor-based intelligent automatic gear shifting system that minimizes the physical and cognitive load of gear shifting in manual gear bicycles and also aims to increase riding performance has been developed and tested on a manual bicycle. The system determines the most appropriate gear-shifting decisions autonomously by processing real-time data from sensors that measure parameters such as wheel speed, pedal cadence, and terrain slope. In addition, multiple riding modes (eco mode, normal mode, and sport mode) are defined, providing an experience suitable for user preference or automatically perceived riding conditions. This feature provides a significant advantage in terms of both saving energy and increasing user comfort. In addition, the fact that the system is low-cost and can be easily installed on any manual-gear bicycle makes it possible for it to appeal to a wide range of users.

The contributions of this paper are summarized as follows:

- This study presents a simple but effective algorithm for achieving seamless and efficient gear shifts and a unique mechatronic system design that will enable this algorithm.

- It includes adaptive riding modes (Standard, Eco, Sport) for personalized and environment-specific gear shifting.

- It delivers a lightweight, cost-effective, and modular system that can be easily integrated into existing bicycles, ensuring accessibility and ease of use for a wide audience.

The structure of this paper is organized as follows: Section 2 details the mechanical and electronic design of the system. Section 3 covers the mathematical model, control mechanisms, and algorithms implemented. The experimental tests and their outcomes are discussed in Section 4. Finally, Section 5 presents the conclusions drawn from the study and outlines potential directions for future research.

2. MECHANICAL AND ELECTRONIC DESIGN (MEKANİK VE ELEKTRONİK TASARIM)

In this section, to carry out the system's mechanical design correctly and efficiently, the electronic components to be used were first defined, and a bicycle model suitable for integrating these components was designed. The visual representation of this bicycle, modeled using SolidWorks software, is presented in Figure 1.

Figure 1. Bicycle design (Bisiklet tasarımı)

The developed system consists of three basic modules that work in an integrated manner. The first module consists of the main body module, which contains the actuators, control unit, and electronic components, and is designed to be compatible with the water bottle positioning area of all bicycle models. The second module includes an information display positioned on the handlebar and provides the user with instant data tracking. The third module consists of Hall effect sensors (KY-003) positioned to measure the rotation speed of the pedals and wheels. This modular structure is designed to increase the flexibility of the system and its compatibility with different types of bicycles.

The main body module, designed to be integrated into all types of bicycles, contains two actuators (HS-755MG) to perform gear-shifting operations. On the actuator, there are gear adjustment levers and two shift cables fixed to them. These levers allow the gear to be increased or decreased by manipulating the shift cables. There is also an IMU sensor (MPU6050) in the main body module to ensure that the system can effectively perform automatic gear shifting in various road scenarios by receiving instantaneous acceleration and slope data. The main body module of the developed system is shown in Figure 2.

Figure 2. Main body module (Ana gövde modülü)

The information display integrated on the handlebar conveys critical riding parameters such as the bicycle's gear status, speed, and inclination to the user during the ride. Instant acceleration and slope data are obtained from the MPU6050 sensor module, while gear information is obtained through Hall effect sensors, and this data is visually presented to the driver via the Organic Light-Emitting Diode (OLED) display. The OLED display is controlled via the Arduino Nano microcontroller with a ready-made OLED library using the I²C protocol and functions as a human-machine interface (HMI) that provides feedback to the driver. This structure aims to optimize the interaction between the driver and the system while enhancing the overall riding experience. The designed information display is shown in Figure 3.

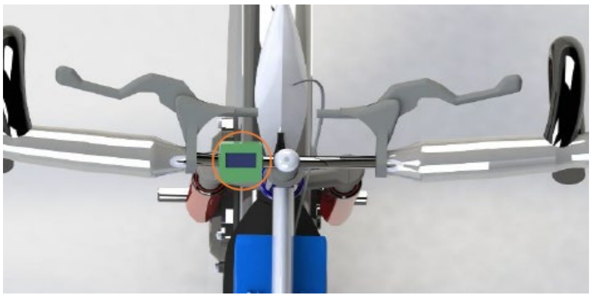

Figure 3. Information display (Bilgi ekranı)

To measure the revolutions per minute (RPM) values of the back and front derailleur, two magnets, one fixed to the rim of the back wheel and the other to the crank arm of the bicycle, and two Hall effect sensors fixed parallel to the body of the bicycle are used. The magnets enable the measurement of revolutions by triggering the sensors at each revolution. Since different riding scenarios (like riding downhill without pedaling) needed to be evaluated, both pedal and wheel revolutions were measured. In this direction, the sensors and magnets are positioned to collect data bi-directionally. The positions of the magnets and sensors on the bicycle are shown in Figure 4.

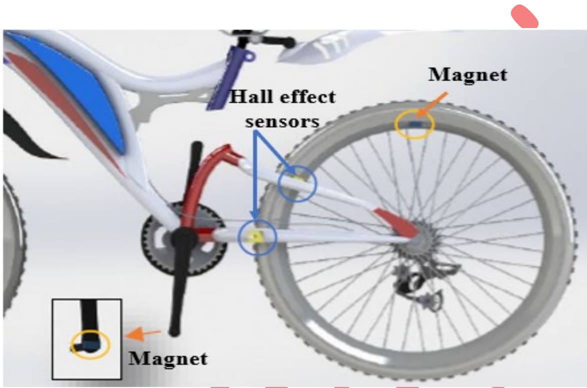

Figure 4. Positions of the magnets and Hall effect sensors (Mıknatıs ve Hall etkisi sensörlerinin konumları)

The final positions of the AMT system, consisting of the main body module, information display, Hall effect sensors, and magnets on a bicycle, are shown in Figure 5 [20].

Figure 5. General components of the system (Sistemin genel bileşenleri)

The developed device was fabricated using 3D printing technology with various thermoplastic materials. This technology enables the rapid and cost-effective production of parts with complex geometries. Furthermore, it allows for easier design modification implementation than traditional manufacturing methods. The main body module, information display, and sensor apparatus of the AMT system were manufactured using Tough PLA material. The material used in producing the gear adjustment levers on the actuator is important in providing an efficient system for power transfer. Therefore, in producing these parts, the PC/ABS FR material, which offers high strength and wear resistance, has been preferred [21]. In post-production, any observed defects in the components were rectified to ensure proper system functionality.

The electronic design of the system developed in this study has been carried out in detail to ensure the harmonious operation of integrated components and to optimize system performance. A special circuit board has been designed and manufactured on the EAGLE platform for the integration of electronic components. The power supply of the system is provided by an 11.1 V lithium polymer battery located in the main body module. A voltage measuring device and a buzzer have been integrated into the system to prevent damage to the lithium polymer battery due to over-discharging and to extend its service life. These components provide an audible warning to the user when the battery falls below the critical threshold value, ensuring that the battery is charged on time. In addition, a voltage regulator is used in the system to reduce the voltage provided by the power supply to the levels required by the actuators and other electronic components. The control unit of the system is built on the Arduino Nano microcontroller. Arduino Nano was preferred because it is suitable for 5V operating voltage and supports analog data reading and I²C communication. Furthermore, the fact that it has a compact size that will fit into the limited space of the bicycle and that it offers a sufficient number of pins for the study are the reasons for this choice. This microcontroller processes the input data, executes the gear-shifting algorithm, and provides overall system control. The information display used for user feedback communicates with Arduino Nano via I²C protocol and acts as a human-machine interface (HMI). The OLED screen visually presents the necessary information to help the user understand the status of the system and make informed decisions while riding.

The sensor infrastructure of the system is designed to collect data suited to various riding scenarios and to develop decision-making mechanisms that ensure safe riding. The MPU6050 sensor card, which is a six-axis inertial measurement unit (IMU), communicates with the microcontroller via the I²C protocol and measures slope, yaw, and roll movement values. This data is used to increase riding safety by restricting gear changes, especially in risky situations such as cornering. The cadence values (revolutions per minute) of both the pedals and the wheels are measured using two Hall effect sensors and two magnets. These sensors read one value from the integrated magnets every time they rotate. These measurements are critical for evaluating riding performance and supporting the system's algorithm. The flow chart of the electronic components of the system is shown in Figure 6.

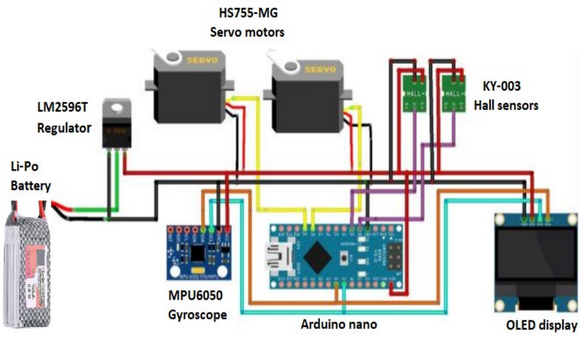

Figure 6. Flow chart of the electronic components
(Elektronik bileşenlerin akış şeması)

3. MATHEMATICAL MODEL, CONTROL STRATEGY, AND ALGORITHMIC DESIGN
(MATEMATİKSEL MODEL, KONTROL STRATEJİSİ VE ALGORITMA TASARIMI)

3.1 Mathematical Model and Control Strategy
(Matematiksel Model ve Kontrol Stratejisi)

The operational algorithm of the system is based on a closed-loop feedback mechanism, with the gear-shifting process being controlled and regulated by this mechanism (Figure 9). The system determines the appropriate gear by analyzing data collected from sensors, including the wheel's revolutions (n), the pedal's cadence (p), and the bicycle's slope angle value ($\%\delta$). Under normal conditions (on a flat route), a typical pedaling cadence required to propel the bicycle is around 80 revolutions per minute. In first gear, a single pedal revolution generally results in the wheel completing approximately 0.5 to 0.7 revolutions. These values are subject to change based on the specific gear ratios and wheel dimensions of the bicycle.

The relationship between the wheel's revolutions (n), the pedal's cadence (p), and the gear configuration is defined by Equation 1, where α and β denote the front and back gear ratios, respectively. This equation establishes a specific range for n based on the input parameters. If the computed value of n falls below the lower threshold of the range, a gear downshift is initiated to optimize performance. Conversely, if the calculated value surpasses the upper threshold, a gear upshift is executed to maintain the desired operational efficiency.

$$n = \mathrm{p}\,\alpha\,\beta \tag{1}$$

The ratio (r) utilized to determine the required range of wheel revolutions is calculated using Equation 2. This ratio serves as a critical parameter for converting pedal cadence into wheel revolutions. Furthermore, the r ratio, as defined in Equation 2, varies across different gear transitions, thereby facilitating the optimization of gear-shifting operations.

$$r = \frac{\alpha}{\beta} \tag{2}$$

The maximum and minimum revolution values of the wheel, based on the pedal cadence and the current gear ratios, are calculated using Equations 3 and 4, respectively. In these equations, r_{new} represents the gear ratio after a gear shift, while $r_{current}$ denotes the gear ratio before the shift. These values facilitate the determination of the required wheel revolutions for transitioning to a higher or lower gear and enable the calculation of speed ranges corresponding to different gear levels.

$$n_{max} = [pr_{current}] + \left[p\frac{(r_{new} - r_{current})}{2}\right] \tag{3}$$

$$n_{min} = [pr_{current}] - \left[p\frac{(r_{new} - r_{current})}{2}\right] \tag{4}$$

On sloped routes, there are significant changes in the pedal cadence (80 revolutions per minute) and the number of revolutions the wheel should have in the relevant gear, which are determined as standard for slopeless routes. These changes are meticulously analyzed by the system to mitigate speed fluctuations caused by slopes and to optimize riding performance. The system precisely detects the slope range of the route through the acceleration sensor with slope detection capability. Based on the slope data obtained by this sensor, an effect coefficient is calculated to compensate for the difference between the speed that should be achieved on sloped ground and the ideal speed on flat ground. In the formula shown in Equation 5, the coefficient k represents the correction ratio required to compensate for the slope effect of the system, while δ represents the percentage slope of the route [22]. This approach allows the ideal speed and gear control to be dynamically realized to optimize both performance and safety while riding.

$$k = \frac{1}{e^{(-0.04*\delta)}} \tag{5}$$

The effect coefficients corresponding to slope ranges between 0% and 45% are detailed in Table 1. These coefficients are applied by multiplying them with the pedal cadence to dynamically adjust the required range of wheel revolutions for gear shifting, particularly during uphill or downhill riding scenarios [23]. The determination of these coefficients is influenced by external factors such as the rider's selected riding mode, targeted calorie expenditure, and desired riding performance. When the rider opts for the standard riding mode, the system employs the coefficients presented in Table 1 as the effect multiplier [22]. This approach ensures that gear shifts are carried out in full harmony with the dynamic requirements of the road and the rider's preferences, increasing riding performance and making energy use more efficient.

Table 1. Slope ranges and effect coefficients for the standart mode (Standart mode için eğim aralıkları ve etki katsayıları)

Slope Range	Effect Coefficient
%0 - % 5	1.00
%5 - %10	1.22
%10 - %15	1.49
%15 - %20	1.82
%20 - %25	2.23
%25 - %30	2.72
%30 - %35	3.32
%35 - %40	4.05
%40 - %45	4.95

In the case where the driver opts for the eco mode, the effect coefficients used in the standard riding mode are reduced by 10%, providing smoother acceleration and easier gear shifts. This riding mode is designed specifically for users who aim to minimize physical effort levels and, therefore, drive at lower heart rates. When evaluated from an energy efficiency perspective, the Eco mode regulates the operating characteristics of the powertrain by limiting unnecessary torque fluctuations and aggressive gear changes and provides a more balanced drive torque. This optimization allows the bicycle to exhibit more stable and gradual acceleration by avoiding sudden power demands, both reducing energy consumption and minimizing the physical load on the driver. The effect coefficients for the eco mode are presented in Table 2.

Table 2. Slope ranges and effect coefficients for the eco mode (Eko modu için eğim aralıkları ve etki katsayıları)

Slope Range	Effect Coefficient
%0 - % 5	1.00 x 0.90 ≅ 0.90
%5 - %10	1.22 x 0.90 ≅ 1.10
%10 - %15	1.49 x 0.90 ≅ 1.34
%15 - %20	1.82 x 0.90 ≅ 1.64
%20 - %25	2.23 x 0.90 ≅ 2.01
%25 - %30	2.72 x 0.90 ≅ 2.45
%30 - %35	3.32 x 0.90 ≅ 2.99
%35 - %40	4.05 x 0.90 ≅ 3.65
%40 - %45	4.95 x 0.90 ≅ 4.46

On the other hand, in riding scenarios where high performance is prioritized, the sport mode is activated to increase the bicycle's dynamic responsiveness. Unlike Eco mode, this mode increases the effect coefficients by 15%, creating a riding characteristic that offers a more aggressive acceleration profile and instant torque response. This mode, which responds more sensitively and quickly to driver inputs, is optimized especially for users who demand high pedal forces and sporty acceleration. Thus, the riding experience becomes more dynamic and performance-oriented, and the powertrain works more efficiently, improving the response time of the vehicle. The effect coefficients determined for this mode are presented in detail in Table 3.

Table 3. Slope ranges and effect coefficients for the sport mode (Spor modu için eğim aralıkları ve etki katsayıları)

Slope Range	Effect Coefficient
%0 - % 5	1.00 x 1.15 ≅ 1.15
%5 - %10	1.22 x 1.15 ≅ 1.40
%10 - %15	1.49 x 1.15 ≅ 1.71
%15 - %20	1.82 x 1.15 ≅ 2.10
%20 - %25	2.23 x 1.15 ≅ 2.56
%25 - %30	2.72 x 1.15 ≅ 3.13
%30 - %35	3.32 x 1.15 ≅ 3.82
%35 - %40	4.05 x 1.15 ≅ 4.66
%40 - %45	4.95 x 1.15 ≅ 5.69

The differentiation in the effect coefficients across various riding modes is rooted in fundamental physiological and biomechanical principles governing human energy expenditure. Scientific studies have established that the metabolic cost of physical activity is directly correlated with heart rate and exertion levels [24]. This relationship underscores the rationale behind the parameter adjustments in different riding modes. In Eco Mode, the primary objective is to optimize efficiency by minimizing physical exertion, thereby reducing metabolic demand and promoting a smoother, less strenuous ride. The 10% reduction in effect coefficients is calibrated to achieve this balance, ensuring that acceleration and gear shifts occur with minimal physiological impact while maintaining sufficient power transfer. Conversely, Sport Mode is engineered to enhance performance by increasing the system's responsiveness to the driver's input. The 15% increase in effect coefficients is strategically determined to amplify acceleration dynamics and torque responsiveness, reflecting the heightened physical engagement required for high-performance cycling. These calibrated adjustments in gear shift thresholds align the system's behavior with the intended physiological and mechanical demands of each mode, thereby optimizing both driver experience and energy utilization.

3.2 Algorithmic Design (Algoritma Tasarımı)

The developed AMT algorithm prioritizes user safety by subjecting instantaneous acceleration, slope, and speed data to a multi-layered validation process. The pedal and wheel speed data, measured using Hall effect sensors, are compared with instantaneous acceleration values obtained from the MPU6050 sensor to confirm that the bicycle's motion results from wheel rotation. This approach prevents gear transitions from causing damage to the drivetrain and motor system in scenarios where the bicycle is being carried or the wheels are not in motion. In addition, the bicycle's yaw and roll movements are monitored using the MPU6050 sensor, and driver safety is enhanced by limiting gear shifts in high-risk situations, such as bends. To identify a situation classified as a risk, it is first necessary to define the movements [25]. As illustrated in Figure 7 (a), roll motion typically refers to the slope movement of the bicycle that occurs due to angular momentum during cornering. In contrast, yaw motion, depicted in Figure 7(b), is characterized by the lateral rotation of the bicycle that occurs during turns. Both movements introduce distinct risks, each requiring careful consideration in gear shifting. The first risk arises from bicycles relying on pedal motion for movement, and gear shifting is impossible without pedaling. During the roll motion, the bicycle is tilted, making pedal movement impossible. In such a scenario, gear shifting should be avoided.

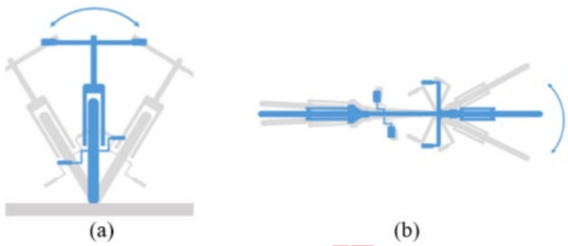

Figure 7. Roll (a) and yaw (b) movement (Yuvarlanma ve sapma hareketi)

The second risk is related to the effects of yaw motion. Some studies have demonstrated that at high speeds, bicycles experience significant aerodynamic forces during yaw motion, which directly impact the bicycle's stability (Figure 8) [26]. In such instances, shifting gears to a lower setting can serve as an effective strategy to counteract instability and enhance control. However, upshifting should be actively avoided, as it may exacerbate the aerodynamic forces, further destabilizing the bicycle and posing potential health risks to the driver.

Figure 8. Yaw movement effect (Sapma hareketi etkisi)

Another critical factor to be considered during gear shifting is the rotation of the pedal while the gear change occurs. The interaction between the pedal and the wheel is controlled by a two-stage control mechanism. This mechanism constantly monitors the speed of the wheel and the movement of the pedal, ensuring that both components work in harmony. Under specific conditions, such as when descending a slope, the wheel may rotate at a speed greater than normal. In this case, if the wheel's rotational speed surpasses a predefined threshold, the pedal's movement is monitored. If the pedal is rotating, the gear is either increased or decreased; otherwise, no gear shift occurs. This method enhances the safety and efficiency of the system during riding, providing the driver with a smoother and more controllable experience. Figure 9 illustrates the flowchart that outlines the automatic gear-shifting algorithm implemented in the developed AMT system. Initially, the algorithm gathers data on wheel speed, pedal cadence, and slope values to enhance the bicycle's overall performance. The slope value is assessed by comparing it against predefined slope intervals, determining which interval the current slope falls into. Based on this comparison, an effect coefficient is obtained. This coefficient helps establish new boundaries for the speed range, setting lower and upper limits for the optimal speed values. Subsequently, it is checked whether the calculated values, based on wheel speed and pedal cadence, fall within the defined range. If the pedal remains stationary despite the values being within or below the acceptable range, no intervention is made. On the other hand, if the pedal cadence value is higher than it should be, the gear is increased; If the pedal is rotating, the gear is lowered. This algorithm operates in a continuous loop, autonomously carrying out gear shifts to ensure optimal performance. Through this method, the system significantly improves both the bicycle's riding efficiency and the user's comfort by selecting the most suitable gear based on varying slope and speed conditions.

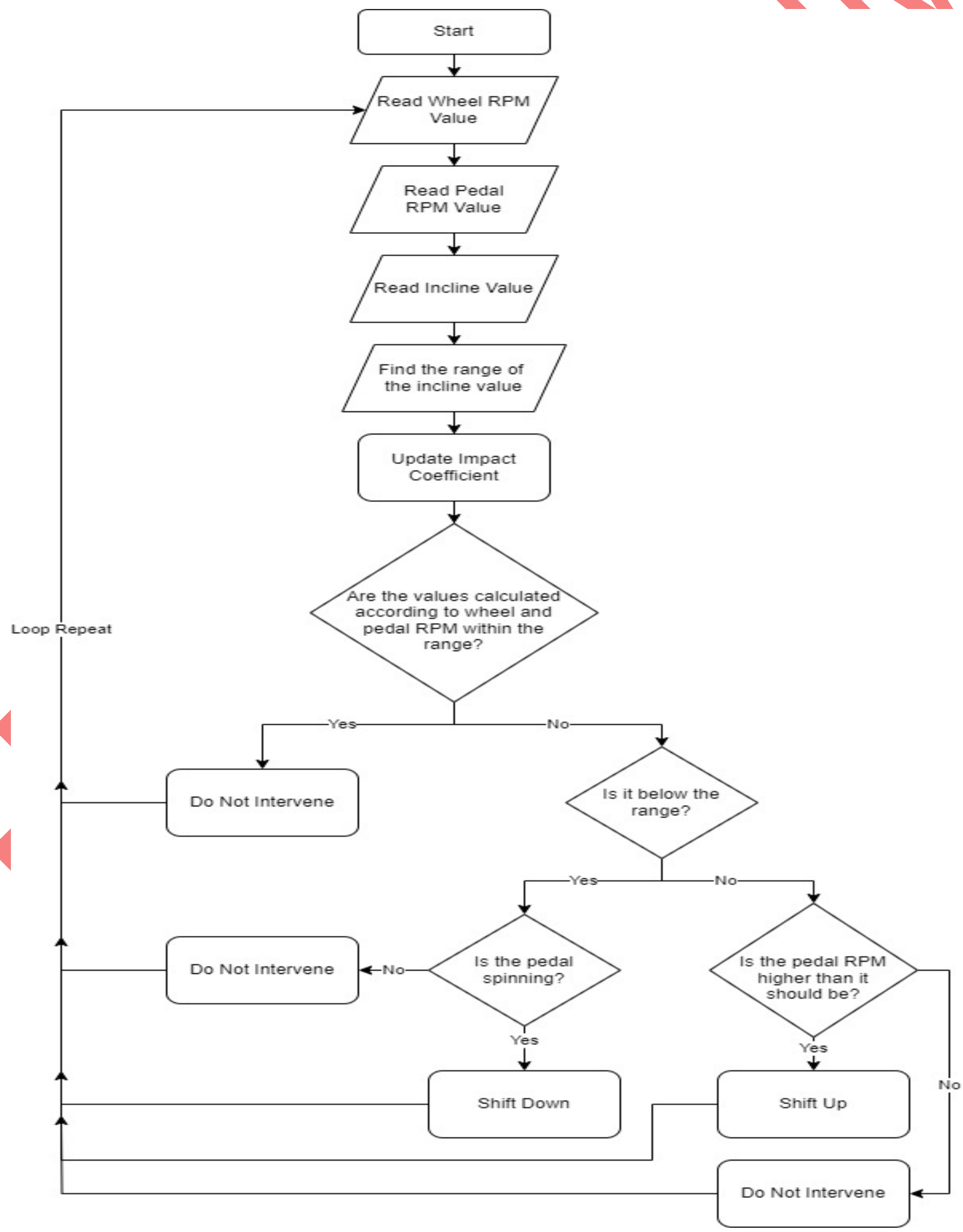

Figure 9. The algorithm flow chart of the AMT system (AMT sisteminin algoritma akış şeması)

4. TESTS AND RESULTS (TESTLER VE SONUÇLAR)

Within the scope of this study, a suitable bicycle selection was made to ensure the applicability and accuracy of the tests. In this direction, a Salcano brand NG700 model bicycle with a total of 21 gears, three front and seven back gears, was preferred. After the mechanical and electronic components were integrated into the selected bicycle, comprehensive tests were conducted to evaluate the system's performance and functionality. The tests in question were divided into three main categories: motor performance evaluation, examination of the accuracy of the Hall effect sensor, and testing of the implemented algorithm. Each category aims to increase the overall reliability and efficiency by analyzing certain aspects of the system.

4.1 Motor Performance Test (Motor Performans Testleri)

The motor performance test involves a series of evaluations to analyze the developed AMT system's efficiency and reliability under varying operational conditions. Initially, a dedicated test platform was constructed to assess motor performance directly on the bicycle, as illustrated in Figure 10.

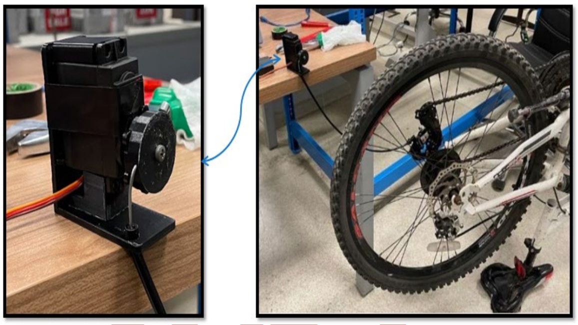

Figure 10. Motor test platform (Motor test platformu)

This platform enabled the evaluation of whether the engine power and energy output were sufficient to facilitate smooth and effective gear shifting. During the tests, several issues were identified, including corroded and stiff mechanical components of the selected bicycle that hindered smooth operation, insufficient current supplied to the motor, and inadequate motor torque. To overcome these challenges, firstly, all mechanical components were inspected, and rusty areas were cleaned with specialized solvents. Then, the required current value for the system was determined, and the power supply that would provide this value was used. Finally, the original motor was replaced with a higher-torque model to ensure sufficient force for effective gear shifts. Through these modifications, the developed AMT system has successfully performed optimal gear-shifting before being mounted on the bicycle.

4.2 Hall Effect Sensor Test (Hall Etkisi Sensörü Testi)

A special test mechanism was designed to determine the bicycle cadence and test the accuracy of the Hall effect sensor. One of the key components of this mechanism, the magnet mounted on the pedal crank, passes in front of the Hall effect sensor with each pedal rotation, triggering a change in the magnetic field. The sensor detects this change and generates an electrical signal. These signals are then counted by the Arduino Nano microcontroller, and the RPM value is calculated. During the tests, pedaling was performed at different speeds to evaluate the accuracy of the sensor, and it was observed whether the sensor made accurate measurements at various speed ranges. In addition, the data obtained from the sensor was compared with the manually determined cadence values , and their accuracy was examined. The obtained results were compared with the Hall effect, confirming that the sensor can measure cycling cadence accurately and reliably. Figure 11 illustrates the test platform used to measure the speed value using the Hall effect sensor.

Figure 11. Hall effect sensor test platform (Hall etkisi sensörü test platformu)

4.3 Algorithm Test (Algoritma Testi)

To evaluate the performance of the control algorithm of the developed AMT system, data was collected from all sensors integrated into the system. These data were displayed on the information display to verify the real-time information delivery to the user. The ability of the Arduino to process data from the sensors and execute the gear-shifting algorithm was tested. In the tests, how quickly and accurately the algorithm responded to various riding conditions, the accuracy of the data provided by the MPU6050 and Hall effect sensors, and how well the measured values of these sensors matched the algorithm's predictions were analyzed in detail. The test results successfully verified not only the algorithm's performance but also the entire system's integrated working capacity. Algorithm tests performed on the bicycle are shown in Figure 12.

Figure 12. Algorithm tests (Algoritma testleri)

The test results for determining the front and back gear levels based on pedal and wheel cadence values for sport mode, standard mode, and eco mode are presented in Tables 4, 5, and 6. These data allow for evaluating the system's performance under various riding conditions and analyzing the algorithm's accuracy. The comparative analysis of these modes reveals significant differences in the system's response characteristics. In sport mode, where the effect coefficients are increased by 15%, the wheel cadence exhibits the highest values for a given pedal cadence, indicating a more aggressive acceleration profile and a faster torque response. In contrast, the standard mode provides a balanced response, ensuring a smooth yet responsive riding experience. On the other hand, with its 10% reduction in effect coefficients, the eco mode results in the lowest wheel cadence values for the same pedal input, demonstrating a controlled and energy-efficient performance. These variations validate that the system adapts to different riding demands, optimizing powertrain behavior. Figure 13 illustrates the wheel speeds achieved in response to the same pedal input for all three riding modes, and how the system dynamically adjusts gear selection to ensure power transmission. The upper graph compares the relationship between pedal and wheel cadence, showing that higher wheel speeds are achieved in sport mode. The lower graph shows how the system optimizes the back gear position in response to changing wheel speeds, revealing how the shift strategy is shaped depending on the riding mode.

Table 4. The front and back gear levels based on pedal and wheel cadence values for the sport mode (Spor modu için pedal ve tekerlek kadans değerlerine dayalı ön ve arka vites seviyeleri)

Pedal Cadence	Wheel Cadence	Front Gear	Back Gear
70	56	1	1
110	88	1	1
80	88	1	2
110	125	1	2
78	125	1	3
90	144	1	3

Table 5. The front and back gear levels based on pedal and wheel cadence values for the standard mode (Standart mod için pedal ve tekerlek kadans değerlerine dayalı ön ve arka vites seviyeleri)

Pedal Cadence	Wheel Cadence	Front Gear	Back Gear
70	49	1	1
110	77	1	1
80	77	1	2
110	109	1	2
78	109	1	3
90	125	1	3

Table 6. The front and back gear levels based on pedal and wheel cadence values for the eco mode (Eko modu için pedal ve tekerlek kadans değerlerine dayalı ön ve arka vites seviyeleri)

Pedal Cadence	Wheel Cadence	Front Gear	Back Gear
70	44	1	1
110	69	1	1
80	69	1	2
110	98	1	2
78	101	1	3
90	113	1	3

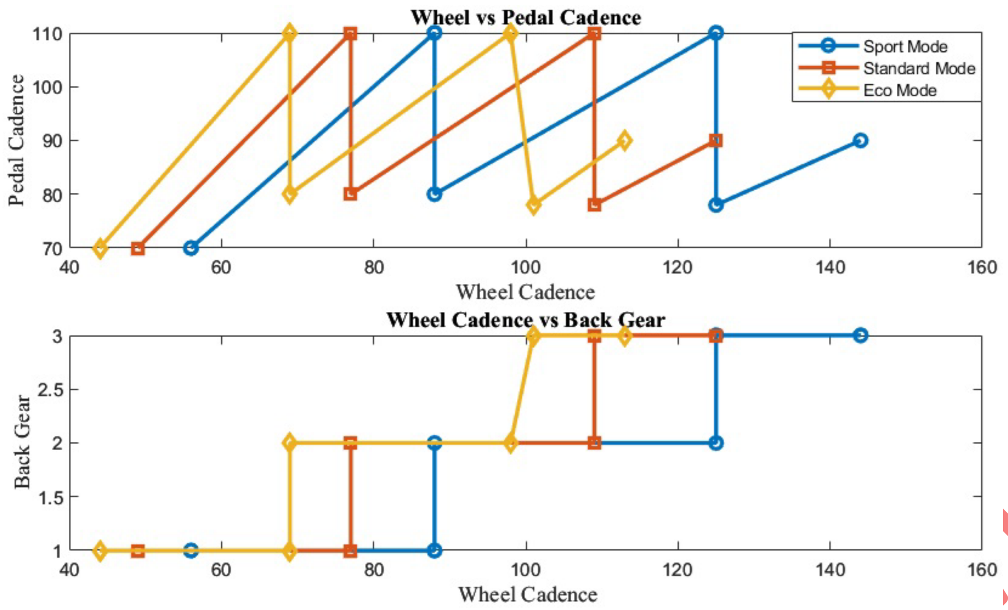

Figure 13. Comparison of wheel-pedal cadence and wheel-back gear across all riding modes (Tüm sürüş modlarında teker-pedal kadansı ve teker-arka dişli karşılaştırması)

Two key performance metrics, Power Transmission Efficiency (PTE) and Stability Index (SI), based on the average wheel-pedal cadence ratio (AWPCR), are presented in Table 7 to strengthen the effectiveness of the system. The PTE metric evaluates how efficiently pedal input is converted into wheel movement, while the Stability Index measures the consistency of gear shifts, analyzing whether sudden changes in speed or torque negatively impact riding comfort and system integrity. According to the table, sport mode demonstrates the highest PTE, while eco mode focuses on energy efficiency, resulting in lower power transmission efficiency. The SI reveals that sport mode provides a more balanced response, whereas eco mode maintains a more controlled performance with a lower SI. As a result, the test results obtained for these three distinct riding modes confirmed that the determined effect coefficients provide the desired contribution to riding dynamics. Thus, the reliability and accuracy of the developed AMT system have been comprehensively proven from both theoretical and practical perspectives.

Table 7. Performance metrics for sport, standard and eco mode (Spor, standart ve eko modları için performans metrikleri)

Mode	AWPCR	PTE (%)	SI
Sport	1.173	116.36	1.916
Standard	1.023	101.49	1.656
Eco	0.921	91.82	1.526

5. CONCLUSIONS (SONUÇLAR)

In this study, an innovative gear-shifting system developed to automate the manual gear-shifting mechanism in bicycles is thoroughly analyzed and presented. The automated gear-shifting process was implemented based on sensor data such as instantaneous slope, acceleration, pedal speed, and wheel speed. The system was designed to offer three different riding modes (Standard, Eco, and Sport) to adapt effectively to user preferences and riding conditions. It was programmed to halt gear transitions when the bicycle was stationary or being transported, thereby preventing potential damage to the drivetrain and motor. Additionally, the bicycle's roll and yaw movement were monitored, and gear transitions were restricted in high-risk situations, such as cornering, thereby contributing to improved driver safety. The reliability and accuracy of the system were evaluated through motor performance tests, Hall effect sensor tests, and algorithm tests. These tests demonstrated that the developed system operates effectively under various conditions, including slope, roll, and yaw movement, and its accuracy was validated through theoretical analysis and practical experimentation.

Future work will focus on further optimizing the sensors and algorithms within the system to enhance its adaptability to individual driver preferences and diverse cycling environments, ensuring more precise and efficient gear shifts.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The authors of this article declare that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarları çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Ahmet KAĞIZMAN: He conducted the literature review, managed the manufacturing and test process, and wrote the article.

Literatür taraması yapmış, üretim ve test sürecini yönetmiş ve makaleyi yazmıştır.

Fehmi Can AY: He conducted the literature review, performed the mechanical design, and checked the manuscript writing.

Literatür taraması yapmış, yazılımı gerçekleştirmiş ve makale yazımını kontrol etmiştir.

Bengisu KILINÇ: She conducted the literature review, performed the electronic design, and checked the manuscript writing.

Literatür taraması yapmış, elektronik tasarımı gerçekleştirmiş ve makale yazımını kontrol etmiştir.

Talha Enes ERCAN: He conducted the literature review, performed the mechanical design, and checked the manuscript writing.

Literatür taraması yapmış, mekanik tasarımı gerçekleştirmiş ve makale yazımını kontrol etmiştir.

Volkan SEZER: He supervised the study and edited the draft.

Çalışmayı yönetmiş ve makaleyi düzenlemiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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