UNIVERSIDAD DISTRITAL FRANCISCO JOSÉ DE CALDAS

Visión Electrónica
Más que un estado sólido
https://doi.org/10.14483/issn.2248-4728

VISIÓN ELECTRÓNICA

A CASE-STUDY VISION

Capture system of horizontal bicycles' kinetic variables for simulation

Sistema de captura de variables cinéticas de bicicletas horizontales para simulación

Santiago Caro-Zapata[1], *Juan Pablo Vasco-Marín*[2], *Daniel Duque-Urrego*[3], *Sofía Catalina Henao-Aguirre*[4], *Jonathan Gallego-Londoño*[5]

INFORMACIÓN DEL ARTÍCULO

Historia del artículo:
Enviado: 10/10/2020
Recibido: 04/11/2020
Aceptado: 17/12/2020

Keywords:
Capture system
Instrumented bicycle
Lineal Potentiometer
Photo-interrupter
Raspberry Pi
Rehabilitation

Palabras clave:
Sistema de captura
Bicicleta instrumentada
Potenciómetro lineal
Foto-interruptor
Raspberry Pi
Rehabilitación

ABSTRACT

In this study, a system has been developed that measures the speed, the turning angle, and the braking force in bicycles or tricycles in static mode. The system also electromechanically controls the resistance to pedaling, opening the possibility of using the system in conjunction with a virtual reality simulator for a computer to offer a new rehabilitation tool for lower limb amputees that use prostheses. The study was divided into two stages. The first was a proof of concept, implemented on a bicycle, evaluating the system requirements, the possible solutions, the necessary couplings for the selected sensors and actuators to test its operation's effectiveness. In the second stage, the system was coupled to a horizontal three-wheeled bicycle with new adjustments and improvements to evaluate its performance. The sensors and actuators implemented, together with the appropriate coupling systems, worked as expected. Hence, a new rehabilitation alternative for amputees is generated based on an appropriate communication protocol with a simulator.

RESUMEN

En este estudio se desarrolló un sistema que mide la velocidad, el ángulo de giro y la fuerza de frenado en bicicletas o triciclos en modo estático, controlando la resistencia al pedaleo electromecánicamente, abriendo la posibilidad de usar el sistema en conjunto con un simulador de realidad virtual para computador, con el objetivo de ofrecer una nueva herramienta de rehabilitación para amputados de miembro inferior que usan prótesis. Se dividió el estudio en dos etapas, la primera fue una prueba de concepto implementada sobre una bicicleta, evaluando los requerimientos del sistema, las posibles soluciones, los acoples necesarios para los sensores y actuadores seleccionados con el fin de evaluar la efectividad del funcionamiento. En la segunda etapa se acopló el sistema a una bicicleta horizontal de tres ruedas mediante ajustes y mejoras, para finalmente evaluar el desempeño del sistema. Los sensores y actuadores implementados, en conjunto con los sistemas de acople apropiados, los cuales funcionaron de acuerdo con lo esperado, de manera que, con un protocolo de comunicación apropiado con un simulador, se genera una nueva alternativa de rehabilitación para amputados.

[1] BSc. (c) in Bioengineering, Universidad de Antioquia, Colombia. E-mail: santiago.caroz@udea.edu.co
[2] BSc. (c) in Bioengineering, Universidad de Antioquia, Colombia. E-mail: juanp.vasco@udea.edu.co
[3] BSc. (c) in Bioengineering, Universidad de Antioquia, Colombia. E-mail: daniel.duqueu@udea.edu.co
[4] BSc. in Mechanical Engineering, Universidad Nacional de Colombia, Colombia. MBA, Universidad EAFIT and HHL – Handleshochschule Leipzig, Colombia and Germany. PhD., Universidad Nacional de Colombia, Colombia. Current position: Assistant Professor at Universidad de Antioquia, Colombia. E-mail: sofia.henao@udea.edu.co
[5] BSc. in Bioengineering, Universidad de Antioquia, Colombia. MSc. in Biomedical Engineering, RWTH Aachen, Germany. MSc. in Bioengineering, Trinity College Dublin, Ireland. Current position: Assistant Professor at Universidad de Antioquia, Colombia. E-mail: jonathan.gallego@udea.edu.co
Cite this article as: S. Caro-Zapata, J. P. Vasco-Marín, D. Duque-Urrego, S. C. Henao-Aguirre, J. Gallego-Londoño, "Capture system of horizontal bicycles' kinetic variables for simulation", *Visión Electrónica*, vol. 14, no. 2, pp. 236-246, July 2020.
https://doi.org/10.14483/22484728.17968

1. Introduction

Worldwide, the estimations stated that 2800 amputations are performed daily [1]. The leading causes are related to vascular diseases from congenital origin, traumatism, or cancer [2]. In Latin America, predictions are that between 0.5 and 1% of the population lives with this condition [3]. Regarding lower limb amputation, the main causes of amputation are the same found worldwide, although, in Colombia, traffic accidents and armed conflict have a significant influence [4].

Prostheses are devices that have shown the best results for the amputee to rehabilitate. However, various physical and psychological factors conduce people to stop using their prostheses [5], [6]. The factors mentioned above are known as adherence problems to the prostheses, and in combination with a sedentary lifestyle of the amputees, shape the reasons why GIBIC Research Group, from the University of Antioquia, proposed to use a horizontal bicycle with three wheels (i.e., tricycle) aiming to train and rehabilitate patients with transtibial or transfemoral amputation. It is expected that such a system could be a new way to improve patients' adherence to their prostheses and increase physical activity from a static, indoor, and controlled space by implementing a virtual reality serious game.

It has been found that using bicycles or tricycles to enhance the physical activity level and to improve adherence increase the muscular strength of both lower limbs, the healthy ones, and the amputee, with low impact on the amputated leg, since most of the bodyweight is deposited over the vehicle's structure, resulting as an excellent tool for rehabilitation [7]. Additionally, virtual reality serious games have shown outstanding effectiveness in cognitive and motor rehabilitation processes [8] Different studies have implemented gait training by virtual reality means, improving the pelvis and hip gait's kinematics, reducing the oxygen consumption, and increasing the vertical symmetry of ground reaction force [9].

The present study was divided into two stages. The first one is called proof of concept and evaluates a system's requirements that allow acquiring kinematic variables of bicycles or tricycles for future interaction with a computer. This information was useful to choose among different kinds of sensors and actuators that could meet the requirements. In the second stage, the tricycle with the new coupling systems was implemented. Several simple tests were made in both stages, and the performance of each system element was analyzed. It was observed that the designed system meets the objective of capturing the signals of interest and controlling the effort on pedaling.

2. Methodology and materials

This study was divided into two stages. A prototype system for capturing and controlling kinematic variables on a conventional bicycle was designed and evaluated in the first stage. Then, in the second stage, the system was improved and adjusted into a three-wheeled horizontal bicycle with the necessary changes and feasible improvements.

2.1. System requirements

Before starting the design stages, an analysis of the requirements of a system capable of acquiring kinematic variables from a bicycle or tricycle was carried out to interact with a virtual reality system for a computer so that the immersion experience could be similar to driving such vehicles in an open field. Kinetic variables that must be measured are presented below.

2.1.1. Bicycle speed measurement without displacement.

Measuring the rear tire speed while pedaling is needed to simulate the virtual vehicle's speed in the computer properly. The back wheel is attached to a fixing cycling roller with an adjustable effort that allows the tire's turn without generating any forward movement.

2.1.2. Handlebar rotation angle measurement

The simulator will allow the user to decide which direction to go inside the virtual environment; therefore, it is necessary to measure the handlebar's rotation angle and direction in real-time.

2.1.3. Braking force measurement

The simulator must detect the bicycle braking action and the magnitude of its force to avoid simulating unexpected movements when it is supposed to be still or decreasing the speed. This stage is needed because the speed sensor has an associated hysteresis that reduces the feeling of response immediately after stopping pedaling.

2.1.4. Pedal resistance control depending on the slope

The simulation may have routes with various slopes. It is proposed that slopes in the virtual environment could be simulated by regulating the roller's effort on which the cycling is assembled. That is why it is required to control the roller's resistance according to the virtual slope's inclination level.

2.1.5. Measuring and control system

It is crucial to have an external system capable of acquiring and processing the sensors' signals, controlling the actuators to regulate the effort, and working as a communication bridge between the simulator and the vehicle to reduce the computational load on the computer executing the graphical simulator processing.

2.2. Stage 1 materials

A conventional two-wheeled mountain bicycle with different speeds was used. Regarding the device that grants the bicycle's fixation, a roller with a mechanically controlled effort regulator with reference TL110 was chosen (Prodalca S.A., Medellín, Colombia) [10]. For speed measuring in bicycles, several methods have been used in the literature, such as GPS, dynamo, or Hall effect sensors [11]. The first one was immediately rejected due to the non-moving operation of the bicycle. The second one was discarded due to the complexity of coupling all the required elements like wave rectifiers, optocouplers and of course the dynamo. Hence, the third option was chosen by its ease of use, low-cost, and accuracy. An A3144 digital output Hall effect sensor was preferred because of its ease of implementation, programming, and because no specific magnetic field values are needed, but only the detection of its presence [12].

In the case of the handlebar rotation angle, not many options were found in the literature. A specific study used inertial measuring units (IMUs) for its detection [13]; another one used an optical system composed of a light source and a camera [11]. IMU was tested but showed much latency. Furthermore, with the handlebar still, the IMU returned an inexistent constant low-speed rotation value requiring additional software processing. Its complexity and size discarded the optical system. Thus, it was decided to use a linear potentiometer mechanically coupled to the handlebar. Despite not finding any bibliographic register of its implementation, its linear resistance dependent only on rotation was the key for this choice.

A servomotor was used to pull a Bowden cable to control the roller's effort resistance to bring a feedback feeling of a virtual slope. This kind of motor was chosen because it has large torque and can stand blocked at a specific position until receiving a signal to change it. Regarding braking measurement, its implementation was carried out during the second stage of the project to prove the concept of capturing variables more easily first. An Arduino UNO, which microcontroller is an ATMEGA 328p, was used as the control system for signals capturing and processing, and actioning actuators [14].

2.3. Stage 2 materials

In this stage, a three-wheeled bicycle was used with more stability and comfort because of its two front wheels, one rear wheel, and a seat with a backrest. This tricycle has an electric motor that allows pedaling assistance to be useful for people with disabilities [15]. Its static operation is guaranteed by the same fixation device chosen in the first stage.

The Hall effect sensor was changed by a TCRT5000 reflective optical sensor with digital output for speed measurement. Even though both sensors operate with different physical phenomena, the same principle is used for their implementation in the measurement of speeds. This change was made due to possible electromagnetic field interference from the electric motor to the Hall effect sensor generating wrong speed measurements. By using a reflective optical sensor, the electromagnetic noise source was discarded.

This device was implemented again during the second stage of the project due to good results obtained with the linear potentiometer for measuring the rotation angle. Similarly, the pedaling resistance control system was kept, but in this case, an HS-485 servomotor was used, which offers a higher torque.

In this stage, it was decided to include the braking force measurement sensor. In the literature, the use of a sliding potentiometer was found for that purpose [11]. However, the potentiometer was discarded because the tricycle has a disc brake, and the system's dimensions do not permit its use. Hence, a piezoresistive flex sensor that changes its resistivity when it is flexed was tested. The sensor was located in the brake lever as a braking force measurement sensor.

Finally, after a bibliography comparison among several devices for the central controlling system, the Raspberry Pi 4 was chosen as the controller, which besides being widely used, is useful in data acquisition in human-powered vehicles [16]. Also, a 16-bit analog-digital converter (ADS1115) was needed because, unlike the Arduino UNO, the Raspberry only allows digital signal inputs. The ADC was used for getting digital values of the linear potentiometer and the flex sensor since their outputs are analog.

2.4. System implementation

2.4.1. Stage 1

Characterization of several properties and limitations of each sensor was done. For example, the maximum distance where the Hall effect sensor can detect the magnetic field presence of a 2cm neodymium magnet, the kind of its output logic (low output when a field is present), the potentiometer transfer function (equation 1).

$$Rotation\ angle = \frac{Value_{ADC} + 6340}{281} \quad (1)$$

With the final purpose of having a conceptual design before creating the coupling parts for sensors and actuators, a 3D design of the bicycle-roller system was made in the Autodesk Inventor software ® (Autodesk, San Rafael, USA), on which the location of the sensor was defined, and the conceptual coupling parts were designed. In Figure 1, the two neodymium magnets' location can be observed, which can be detected by the Hall effect sensor situated in a box attached to the bicycle's upper seat stay. This design looks to guarantee the sensor range detection, allowing the rear wheel speed measurement.

Figure 1. Conceptual design in Autodesk Inventor® of magnet location for the indirect speed measurement and Hall effect sensor location

Source: own.

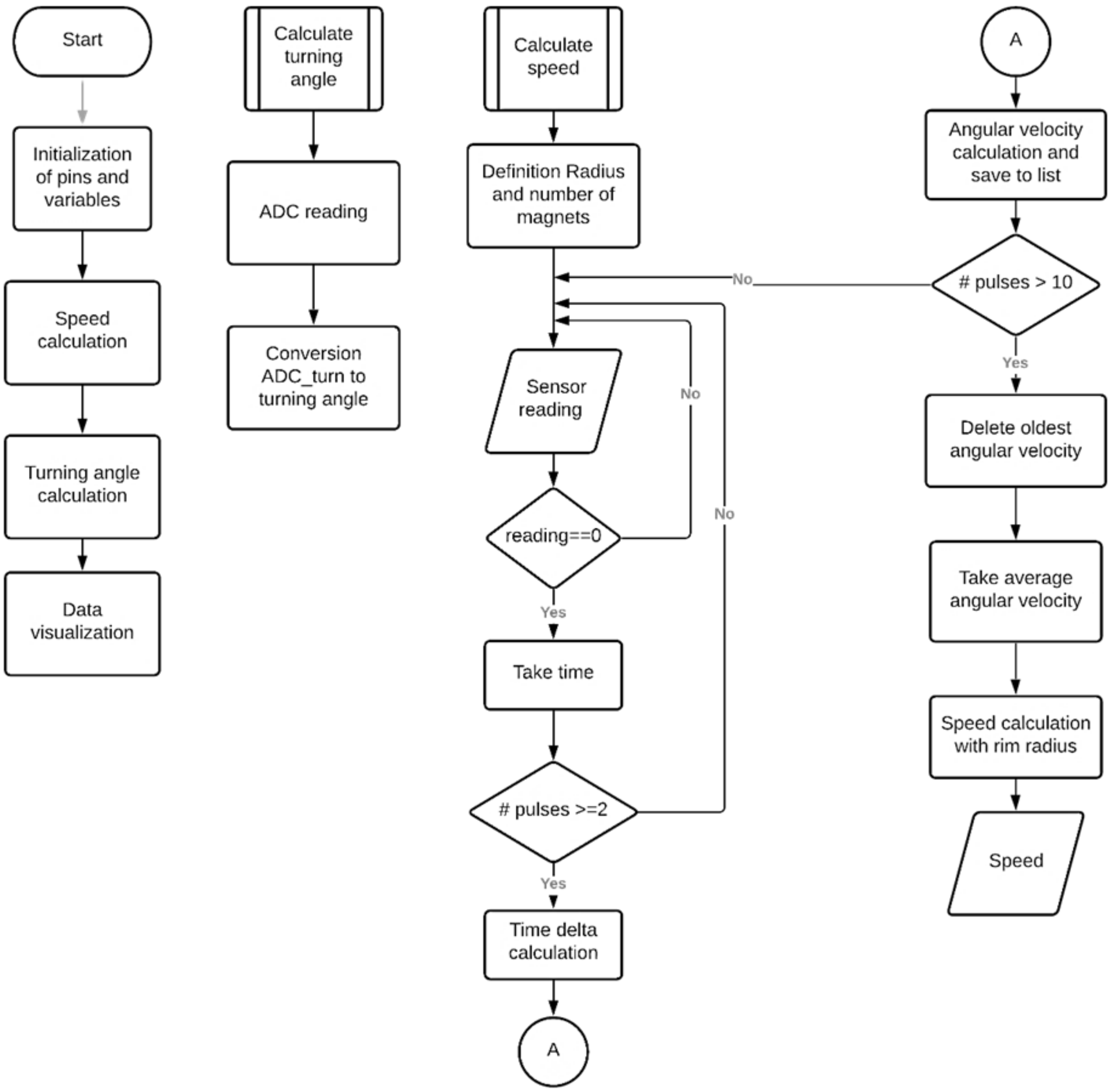
For the correct coupling of the linear potentiometer to the bicycle, a system of two pulleys with the same diameter was needed between the handlebar and the potentiometer located on the frame top tube. Figure 2 shows the coupling system's final implementation highlighting the assembly between the conventional bicycle and roller as well as the general location of measurement and control components. The servomotor was located in a place that allows greater proximity to the mechanical system controlled by the wire that regulates the pedaling resistance offered by the roller.

Figure 2. Implemented system for capturing kinematics variables in a conventional bicycle during static operation. Coupling systems details and elements used are shown (A: Turning angle system, B: Hall effect sensor, C: Servomotor, D: Arduino with display)

Source: own.

The sensors' signal processing to get the required variables was done, as shown in the flow chart of Figure 3. The pulses detected by the Hall sensor are read by the Arduino, which denotes the wheel rotation angle speed. The calculus of raw speed is done using the previously mentioned data and the wheel's radius. The mean speed is obtained using the moving average technique, with nine additional calculated raw speeds [17]. Simultaneously, the ADC value from the potentiometer's pin is registered and converted to degrees through equation (1). The obtained data is shown in a seven-segments display. Finally, a computer visualization system was developed to show the acquired data received from the Arduino UNO through UART communication. This visualization system was made using a Python script that needed PySerial [18] and DrawNow libraries [19].

Figure 3. Flow chart of Arduino UNO in stage 1.



Source: own.

2.4.2. Stage 2

As in the previous stage, a characterization of the sensors and other elements was carried out, detecting: the type of photo-switch logic, the communication protocol for the conversion of the ADC using the ADS1115, the percentage ranges of the PWM hardness to control the movement of the servomotor according to the level of effort required to break the roller, the operation of the flex sensor, among others.

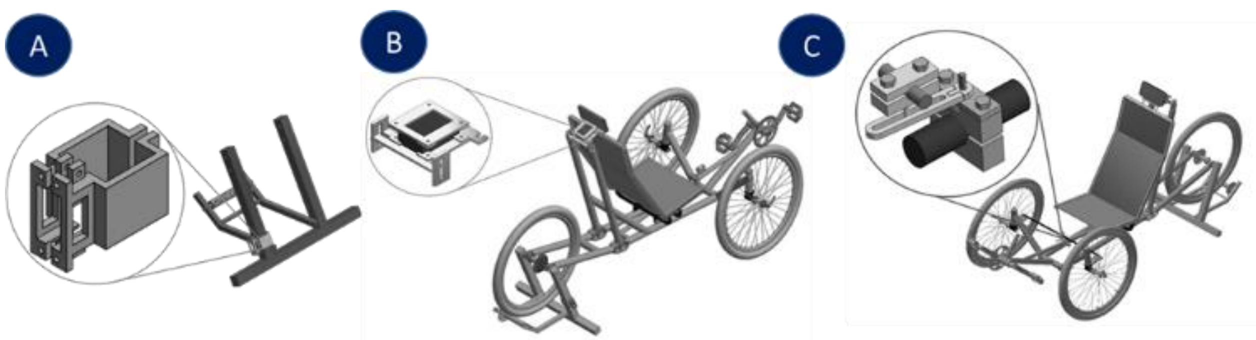
At this stage, new coupling parts were designed due to the drastic change in the vehicle's geometry, such as the steering system; furthermore, the characterization of the sensors, such as the photo-switch, implied a different location. A 3D model of the tricycle-roller system was built in the Autodesk Inventor Software ® in which the location of the components was defined, and their coupling parts were designed. This model was made with the exact measurements to manufacture the necessary couplings through 3D printing.

Regarding the potentiometer, the coupling system and rotation transmission were designed (both can be seen in Figure 4 (C)). That system rotates the potentiometer shaft leveraging it through the displacement of the transmission bar between the wheels. Moreover, a coupling was made to attach the servomotor to the fixing device (Figure 4 (A)). This coupling consists of two pieces that are joined with screws and have a space for the actuator's correct operation. The actuator is controlled by a PWM signal whose duty range was characterized to cover the rotation amplitude required to pull the Bowden cable of the mechanical stress regulation system from the point of zero resistance to the maximum blocking of the bearing.

The Raspberry Pi has a casing attached to the tricycle in a safe and easily accessible place, which is why a supporting element was designed with an optimal location, so the Raspberry is not affected by the tricycle mechanism and the electromagnetic noise as shown in Figure 4 (B).

It was not necessary to design an external coupling for the speed sensor with the photo-interrupter that allows detecting light reflection because the holes in the braking system of the tricycle (i.e., disc brake) were used, and they are equidistant from the wheel's axis of rotation piercing the total thickness of the reflective metal, allowing the sensor to be used as an encoder [20]. In the brake sensor case, an external coupling was not required either, since it was attached to the tricycle brake in such a way that it flexes depending on the force that the person exerts when pressing the brake lever.

Figure 4. Coupling parts for the servomotor (A), the Raspberry (B), and the potentiometer (C). Located in the static device (A) and tricycle (B and C).



Source: own.

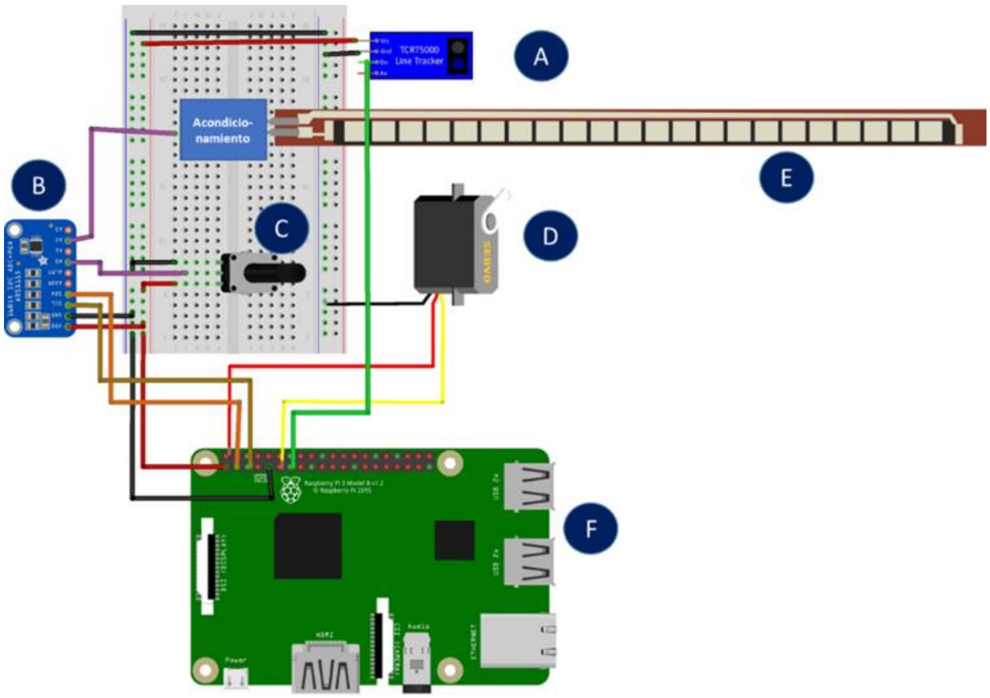
A schematic diagram was designed by implementing a breadboard. This concept can be seen in Figure 5. The diagram includes the Raspberry Pi, the servomotor controlled by PWM signal, the photo-interrupter, the potentiometer, the flex sensor with its conditioning sub-circuit, and the external ADS1115 16-bit converter. The converter receives the analog signals from the potentiometer and the flex sensor, which are sent as digital signals to the Raspberry Pi using the I2C protocol. The whole system's power is supplied by the Raspberry Pi board's regulator, which energy comes from an adapter plugged into the outlet.

A communication protocol was designed (see Figure 6) to exchange information between a computer (i.e., master) and the Raspberry (i.e., slave), in which the master can send two types of instructions to the slave.

The first instruction that can be sent is a "request" for all the kinetic variables (i.e., speed, angle of rotation, and braking force). Then, the slave sends back the data in a concatenated form where it starts with a letter that indicates the variable that is being sent (i.e., "S" for speed, "A" for angle, and "B" for braking), followed by the number of digits that the variable has and, finally, the value of the variable. The sending order is speed, rotation angle, and braking force. At the end of the last digit of the last variable, a "/" is concatenated as a termination character to send the data.

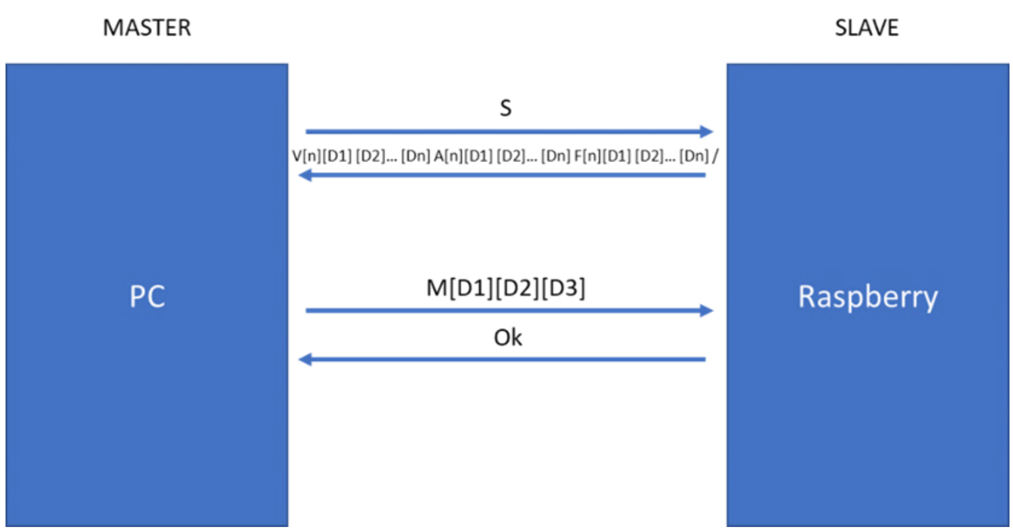
The second instruction is the "slope modification" represented by the letter "M." When the slave receives this instruction; it reads the next available data in the buffer, which corresponds to the increase in the slope angle (or resistance to pedaling) that must be modified by the Raspberry Pi, this data is transformed into a duty percentage that modifies the PWM. In turn, the PWM changes the servomotor's rotation angle to adjust the roller's effort and, in this way, simulate the change of slope.

Figure 5. Concept of the system connection diagram and its components. (A) Photo interrupter, (B) ADS1115 ADC converter, (C) Linear potentiometer, (D) Servomotor, (E) Flex sensor, (F) Raspberry Pi.



Source: own.

Figure 6. The communication protocol between Raspberry and computer.



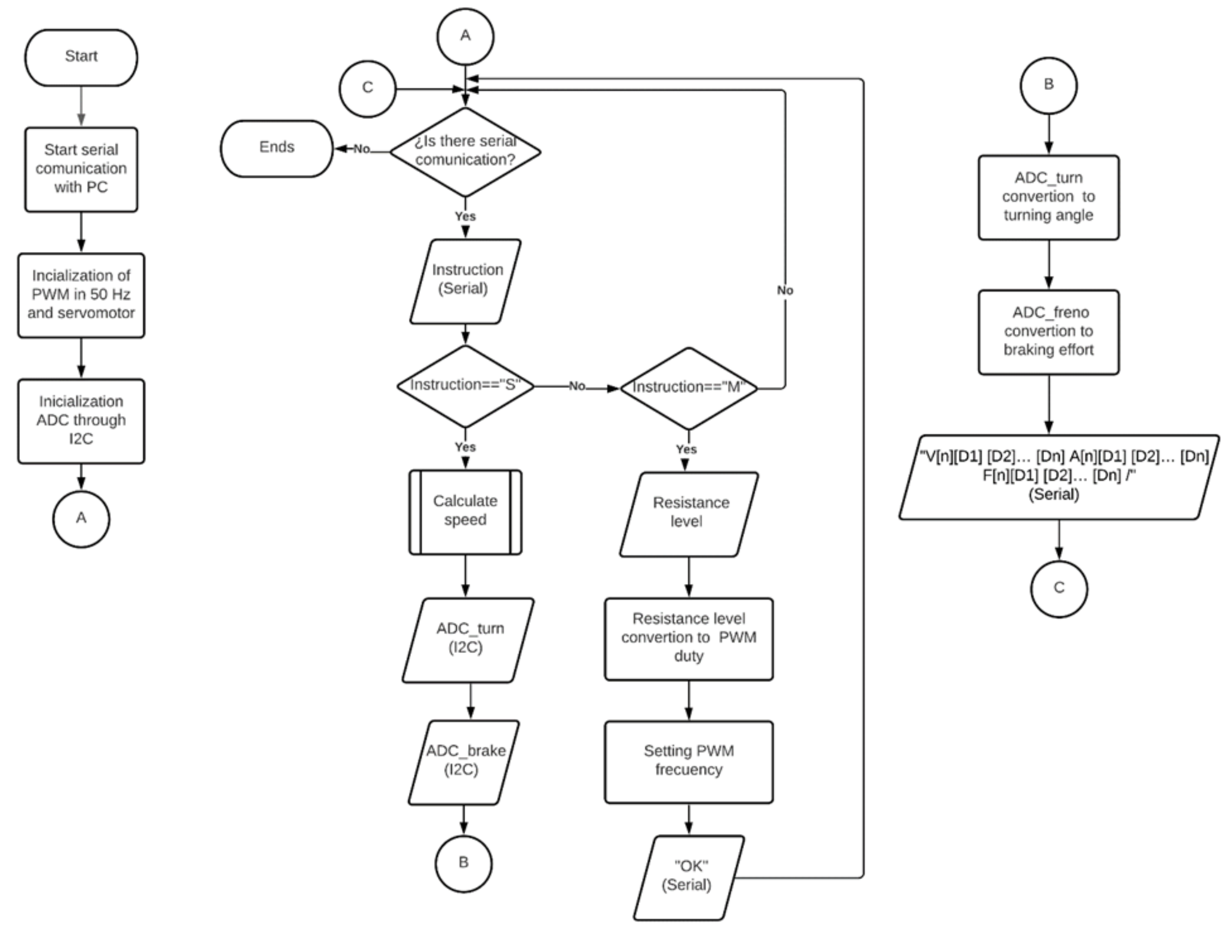
Source: own.

With the communication protocol defined, the operating algorithm was designed inside the Raspberry (Figure 7), which was programmed with Python. First, the elements and the two types of implemented serial communication (i.e., UART and I2C) are initialized. Then, an infinite cycle is entered where the Raspberry is constantly reading the UART port waiting for one of the instructions to arrive. When the "S" instruction arrives, the Raspberry immediately gets the speed that is calculated with the same principle that was used with

Arduino. Lastly, the ADC is asked to send back the ADC value corresponding to the rotation and the braking force, to finally concatenate the values and send them by serial communication.

Once either of the two tasks is finished, the Raspberry continues reading the UART port waiting for a new instruction.

Figure 7. Raspberry operation flowchart in stage 2.



Source: own.

3. Results and analysis

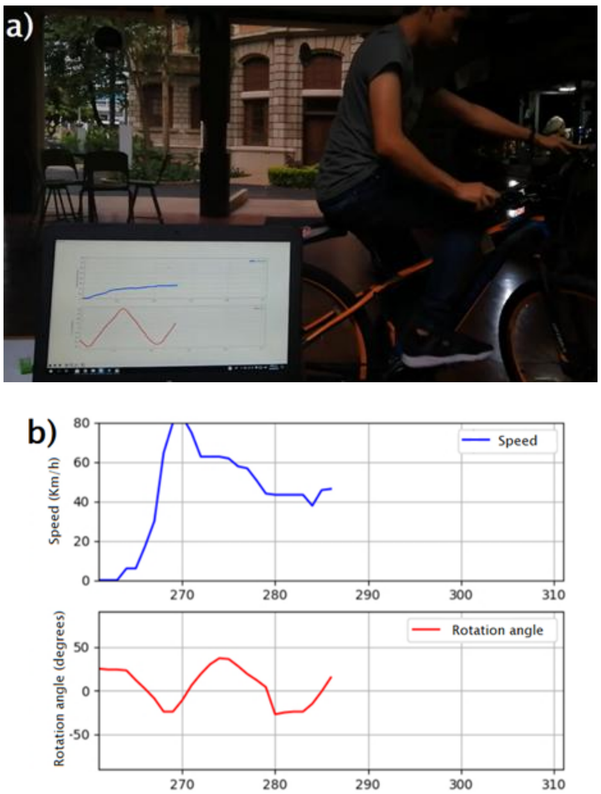
3.1. Stage 1

The A3144 Hall effect sensor used for speed measurement was useful for indirect speed measurement; however, the magnets must be located nearby the sensor so that the magnetic field could be adequately detected. Consequently, an additional piece had to be designed so that the sensor could be approximately 1 cm away from the magnets.

The linear potentiometer turned out to be a useful device for measuring the bicycle handlebar's rotation angle, although its use has not been reported in the literature. The change in resistance of the linear potentiometer behaves as a continuous variable, so there is no minimum resolution, and the rotation of the handlebar is proportional to the rotation of the potentiometer. The coupling system's limitation is the need to have a specific design for the bicycle used in the study, which affects its applicability in other vehicles.

With its 16 MHz, Arduino Uno worked fast enough to perform data collection and calculation of variables. The problem found was in its connection with Python, since this is an interpreter in which incoming data processing was slow, generating a delay in the visualization; this setup increased the system execution time due to filling the Python serial buffer. It was possible to generate a graph that showed the speed and rotation angle in real-time with a delay of 1 s, obtaining the graph that can be seen in Figure 8.

Figure 8. Real-time test of the simulator (A) and graph of speed and angle of rotation of the handlebar (B).



Source: own.

Finally, it was observed that the fixation device, with the modifications made, met the requirements set out to be a training station. This device's advantage is its direct intervention, giving the servomotor an easy coupling to the adjustable effort system.

3.2. Stage 2

The photo-interrupter delivers a low value with a reflective surface, so this was considered when programming the velocity capture processing algorithm. The PMW's duty percentage signal necessary to control the servomotor, in a range of 0° to 180°, should vary between 1% and 12%. This range was a slight variation from the duty's nominal values associated with a servo motor, which, according to the literature, are between 5% and 10%. Regarding the potentiometer as a turning angle meter, the same successful behavior of stage 1 was obtained. However, the tricycle required a completely different coupling system to transmit the steering turn to the potentiometer shaft using a four-bar system, which led to the expected behavior. The range of motion with the new coupling system was approximately 100°, while with stage 1's pulley system, a total range of motion of around 180° was achieved. The tricycle's rotation range is smaller than the conventional bicycle range because it is limited by the contact between the tires and the driver's seat at their full stops.

Regarding the servomotor, it was found that the range of movement generated meets the requirement of displacement of the cable Bowden to bring from zero resistance to absolute blocking with the mechanical system of resistance to pedaling, generating a total shortening in the cable Bowden of approximately 2cm.

The speed and braking measurement systems, which did not require coupling systems, were successfully placed with adherent elements to be tested on their function. The photo-interrupter together with the brake disc and its respective holes in the reflective surface showed a correct speed measurement and a better resolution in time concerning the stage 1 system due to the presence of a higher number of markers that generate more pulses during a complete revolution of the rim compared to the two magnets that functioned as markers in the conventional bicycle.

The flex sensor allowed to correctly measure the braking force made on one of the brake levers; however, a further analog conditioning stage was needed to amplify the ADC input voltage variation to have a better resolution in the measurement.

The communication protocol allows the computer to request information every given amount of time, thus preventing the system from saturating as it happened with the Arduino UNO in stage 1. However, the sampling frequency cannot be too low either because the simulation must be as faithful as possible to reality. Additional system testings are required to determine the optimal variable sampling frequency.

4. Conclusions

Some options are available in the literature for the kinematic and kinetic variables, but not all are optimal for this system. Therefore, the selected sensors are characterized by their simplicity and ease of implementation, without neglecting their precision. According to the literature, some options were not adequate for this system; hence, other alternatives were sought to measure the rotation angle and the braking force.

The measurements made by the selected sensors, although they presented results according to the expectations in terms of their behavior, they were not compared with reference values. From what was previously mentioned, one of the following tasks is to compare the measurements taken by the developed system against measurements from reference systems, to calculate the error, and, subsequently, carry out corrections if necessary.

Coupling the sensors to the different types of vehicles presented certain complications, although their operation should be the same. The complications are caused by the structural differences between the tricycle and the bicycle, making it necessary to design unique couplings depending on which one is being used. For this reason, it was not possible to make a system adaptable to any vehicle.

Finally, it is possible to electromechanically regulate the device's pedaling resistance during static operation using a high torque servomotor controlled through a signal sent from the Raspberry. However, a preliminary characterization of the servomotor's operation is fundamental to match the percentage of hardness with the rotation angle of the motor and, therefore, with the level of effort generated on the roller.

Acknowledgments

We are grateful to Minciencias (previously Colciencias) and the GIBIC group of the University of Antioquia, for the partial funding of this study, contained in the project "Evaluation of a combined strategy to improve the adherence of amputees due to Improvised Explosive Devices (IED) to the use of low-cost lower limb prostheses" within the framework of the national call 808-2018.

References

[1] M. Sereday, M. Damiano, and S. Lapertosa, "Amputaciones de Miembros Inferiores en diabéticos y no diabéti-cos en el ámbito hospitalario," ALAD (Asociación Lartnoamericana Diabetes), vol. XVII, pp. 9–15, 2009, [Online]. Available at: http://www.revistaalad.com.ar/pdfs/0905_Amp_de_Miem.pdf

[2] C. Quintero Quiroz, A. Jaramillo Zapata, M. T. De Ossa Jiménez, and P. A. Villegas Bolaños, "Estudio descriptivo de condiciones del muñón en personas usuarias de prótesis de miembros inferiores", *Rev. Colomb. Médicina Física y Rehabil.*, vol. 25, no. 2, pp. 94–103, 2018. https://doi.org/10.28957/rcmfr.v25n2a1

[3] F. A. Salinas, L. F. Ahunca, D. I. Muñoz, D. A. Vélez, and L. H. Sierra, "Guía de práctica clínica para el diagnóstico y tratamiento preoperatorio, intraoperatorio y posoperatorio de la persona amputada, la prescripción de la prótesis y la rehabilitación integral," *Iatreia*, vol. 29, no. 4, pp. 82–95, 2017.

[4] O. Horgan and M. M. Lachlan, "Psychosocial adjustment to lower-limb amputation: A review", *Disability and rehabilitation*, vol. 26, no. 14, 2004. https://doi.org/10.1080/09638280410001708869

[5] C. H. Caicedo, A. Smida, "Intensidad informacional para la longitudinalidad asistencial en sistemas de salud", *Visión Electrónica*, vol. 10, no. 1, pp. 83–95, jun. 2016. https://doi.org/10.14483/22484728.11612

[6] Colciencias, "Convocatoria para proyectos de Ciencia, Tecnología e Innovación y su contribución a los retos de país- 2018 | Convocatoria 808 | COLCIENCIAS". [Online]. Available at: https://www.colciencias.gov.co/convocatorias/investigacion/convocatoria-para-proyectos-ciencia-tecnologia-e-innovacion-y-su-0

[7] W. L. Childers, R. S. Kistenberg, and R. J. Gregor, "The Biomechanics of Cycling with a Transtibial Amputation: Recommendations for Prosthetic Design and Direction for Future Research", *Prosthet. Orthot. Int.*, vol. 33, no. 3, pp. 256–271, 2009. https://doi.org/10.1080/03093640903067234

[8] I. Pinilla Giménez, "Juego serio para terapias de rehabilitación motora y cognitiva con realidad virtual," Univ. Valladolid. Esc. Técnica Super. Ing. Telecomunicación, 2017. [Online]. Available: http://uvadoc.uva.es/handle/10324/23073

[9] G. Fiedler, J. Akins, R. Cooper, S. Munoz, and R. A. Cooper, "Rehabilitation of People with Lower-Limb Amputations", *Curr. Phys. Med. Rehabil. Reports*,

vol. 2, no. 4, pp. 263–272, 2014. https://doi.org/10.1007/s40141-014-0068-8

[10] Prodalca, "Rodillo personal trainer con regulador de esfuerzo," 2019. [Online]. Available at: https://prodalca.com.co/producto/rodillo-personal-trainer-con-regulador-de-esfuerzo/

[11] C. Sun and Z. Qing, "Design and Construction of a Virtual Bicycle Simulator for Evaluating Sustainable Facilities Design," *Adv. Civ. Eng.*, vol. 18, 2018. https://doi.org/10.1155/2018/5735820

[12] T. Instruments and I. Sloa, "Chapter 16 Active Filter Design Techniques Excerpted from Op Amps for Everyone Literature Number: SLOD006A". [Online]. Available at: https://www.changpuak.ch/electronics/downloads/sloa088.pdf

[13] L. Xiong et al., "IMU-based automated vehicle slip angle and attitude estimation aided by vehicle dynamics", *Sensors*, vol. 19, no. 8, 2019. https://doi.org/10.3390/s19081930

[14] Arduino, "Arduino Uno Rev3 | Arduino Official Store", [Online]. Available at: https://store.arduino.cc/usa/arduino-uno-rev3

[15] S. Sanghani, "Stumps and Cranks: An Introduction to Amputee Cycling", Meyer & Meyer Sport, 2016.

[16] M. Ambrož, "Raspberry Pi as a low-cost data acquisition system for human powered vehicles," *Meas. J. Int. Meas. Confed.*, vol. 100, pp. 7–18, 2017. https://doi.org/10.1016/j.measurement.2016.12.037

[17] F. Villarreal, "Introducción a los modelos de pronósticos," Univ. Nac. del Sur, pp. 1–121, 2016. [Online]. Available at: https://www.matematica.uns.edu.ar/uma2016/material/Introduccion_a_los_Modelos_de_Pronosticos.pdf

[18] Python, "pySerial 3.0 documentation". [Online]. Available at: https://pythonhosted.org/pyserial/

[19] Python, "python-drawnow: MATLAB-like drawnow to easily update a figure". [Online]. Available at: https://github.com/stsievert/python-drawnow

[20] F. W. Sanabria Navarro, J. G. Bustos, W. E. Castellanos Hernández, "Adaptive video transmission over software defined networks", *Visión Electrónica*, vol. 13, no. 1, pp. 152–161, feb. 2019. https://doi.org/10.14483/22484728.14398