Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #46646

Introducing Angle Sensors into Robot Block Teaching Kits Using Non-Contact Magnetic Rotary Encoder

Dr. Sumito Nagasawa, Shibaura Institute of Technology

Prof. Dr. Sumito Nagasawa received Ph.D. in Engineering from the University of Tokyo in 2001. He is a Professor in Department of Engineering Science and Mechanics at SIT. His research interests include miniaturized robots using Micro-Electro-Mechanical Systems technologies and robot education for STEAM.

Prof. Hatsuko Yoshikubo Ph.D., SHIBAURA INSTITUTE OF TECHNOLOGY

Dr. Hatsuko Yoshikubo obtained Ph. D. in English Literature from Chiba University in Japan in 2002. She is currently a Professor of Humanities and a senior departmental administrator, currently attached to the Innovative Global Program in the College of Engineering at Shibaura Institute of Technology, a highly-ranked engineering university in Tokyo. Innovative Global Program (IGP) is an engineering degree program incorporating humanities components, with a student body consisting mainly of international students (https://igp.shibaura-it.ac.jp).

As part of her current role as Deputy Director of the IGP, she is the Principal Investigator for the following research grants: - Japan Society for the Promotion of Science Research: Grant 24K06133 (2024-2027) - Shibaura Institute of Technology Grant for Educational Reform and Research Activity (AY2024).

Her research interests include: (1) Impacts and potential benefits of including humanities components in science and engineering degree programs (2) Innovative methods of assessment in science and engineering education, especially in the context of remote learning, hybrid courses, and collaborative international programs (3) Solving systematic issues that impact the effectiveness of science and engineering education programs, in both in-person and remote learning contexts.

In recent years she has been a presenter at the following international conferences: World Educational Research Association (WERA): WERA Conference 2019, 2022, 2023, 2024 Asia-Pacific Association for International Education (APAIE): APAIE Conference 2022, 2023, American Society for Engineering Education (ASEE): Annual Conference 2022, 2023, 2024 International Institute of Applied Informatics (IIAI): International Conference on Data Science and Institutional Research (DSIR) 2023

Awards: SIT's Presidential Award 2023 ASEE 2023: Multidisciplinary Engineering Division's 'Best Diversity Paper' Award DSIR 2021: 'Outstanding Paper' Award

Introducing Angle Sensors into Robot Block Teaching Kits Using Non-Contact Magnetic Rotary Encoder

Abstract

Rotary encoders are integral components in mechatronics and are widely used to measure shaft angles across various systems. However, integrating them into educational robot block kits poses several challenges. Conventional rotary encoders are costly ($100–$140), bulky due to precision mechanical components and optical systems, and require high torque to rotate their shafts. These characteristics make them unsuitable for educational environments, where simplicity, affordability, and low mechanical load are essential. Furthermore, incremental encoders produce pulse signals that are difficult for beginners to interpret, limiting their educational utility.

This study presents a practical and cost-effective alternative by incorporating a non-contact magnetic rotary encoder into robot block kits. The AS5048B encoder from ams-OSRAM AG was selected for its compact surface-mount design, high angular resolution (14-bit; 0.022° per step), and affordability (approximately $10). Unlike traditional encoders, the AS5048B measures angular position through magnetic field detection without physical contact, and outputs angle data via either I2C digital communication or a PWM signal. Since typical educational kits lack a general I2C interface, the PWM output (1 kHz, 4119 steps) was converted into an analog voltage using a custom-designed RC low-pass filter, ensuring compatibility with conventional analog input systems. The filter was optimized to balance measurement accuracy and response time.

A prototype sensor block was integrated into a robot block kit and tested in an inverted pendulum experiment. The system exhibited stable analog output, with a maximum angular error of ±4.5°, occurring at a 50% PWM duty cycle. These results demonstrate that the proposed encoder solution maintains high precision and reliability while substantially reducing both cost and system complexity. This approach supports real-time feedback control exercises using affordable, beginner-friendly components, thereby enhancing accessibility to hands-on robotics education.

Keywords

Rotary Encoder, Educational Robotics, Inverted Pendulum, Low-Pass Filter

1. Introduction

1.1 Background

Rotary encoders are essential sensors in mechanical engineering and mechatronics, widely used for measuring the rotational angle and speed of shafts [1-2]. However, when these sensors adapt in educational robot applications several challenges have to be solved. This study proposes a novel approach to overcoming these challenges by utilizing a compact, non-contact magnetic rotary encoder. Additionally, preparations are underway to apply our proposed rotary encoder system to university-level educational content, and the outcomes of this effort will be included in our final manuscript.

1.2 Current Status of Educational Materials Using Rotary Encoders

[Applications in University Education]

(i) **Inverted Pendulum**: Rotary encoders are widely reported in educational robot materials, particularly for use in inverted pendulum systems. These systems incorporate foundational topics in control engineering, such as deriving Lagrange equations, linearizing nonlinear motion equations, identifying viscous resistance coefficients, and designing stabilization controls. The inverted pendulum serves as an effective educational tool because it allows students to integrate theoretical understanding with practical application, resulting in high educational effectiveness.

(ii) **DC Motor Characteristic Measurement**: Educational materials often utilize rotary encoders to accurately measure the rotational speed of DC motors. This enables students to study the relationship between rotational speed and back electromotive force (back-EMF). This topic, which targets undergraduate students, is essential for understanding motor characteristics and learning the basics of motion control in the field of mechatronics.

(iii) **Kinematics and Dynamics of Robotic Arms**: As a foundation for robot control, multi-joint robotic systems require precise motion planning for each joint using kinematics, as well as an understanding of real-world dynamics that consider inertial forces. Achieving this requires high-precision measurement of the instantaneous movement of each joint, making rotary encoders indispensable for such systems.

This overview highlights the integral role of rotary encoders in diverse educational contexts, emphasizing their importance in understanding and applying fundamental principles in control engineering and mechatronics.

[Applications in Primary and Secondary Education]

Rotary encoders also hold potential benefits for primary and secondary education by facilitating the understanding of fundamental concepts in robotics and engineering. To explore this potential, submissions to the Idea Contest of the "Universal Robotics Challenge," an international robotics competition for elementary and middle school students where the authors serve as organizers, were reviewed. The review identified several key use cases:

(i) **Monitoring the Opening and Closing of Doors or Gates**: Limit switches and proximity sensors are often used as substitutes for this purpose. While these can determine whether a door or gate is simply open or closed, they cannot measure the degree of opening. Rotary encoders provide a solution for cases where such detailed measurement is required.

(ii) **Measuring the Rotational Speed of Wheels or Motors**: Although reflective sensors or Hall sensors can be used as alternatives, their implementation is complex, accuracy is often low, and programming is challenging. In mobile robots, accurately measuring the current speed is critical. Traditional teaching systems often assume that the command output to the DC motor directly reflects its state. However, due to load variations, this assumption is frequently inaccurate, making it difficult to determine the actual state of the motor. Additionally, in systems addressing environmental issues, such as those that adjust operations based on the rotational speed of wind or water turbines, rotary encoders can replace technical and often cumbersome alternative systems.

(iii) **Measuring the Orientation or Tilt of Robots and Components**: While accelerometers are commonly used to determine orientation by measuring the direction of gravity, they present challenges in terms of setup and data handling. Furthermore, for components rotating on a horizontal plane, orientation cannot be determined based on gravity direction. Rotary encoders overcome these limitations, providing a more straightforward and accurate solution.

These applications illustrate the versatility of rotary encoders in addressing practical challenges in robotics education for younger students, offering an opportunity to introduce advanced measurement techniques at an early stage.

1.3 Technical Challenges of Using Rotary Encoders in Education

The educational use of rotary encoders involves several technical challenges:

(i) **High Cost and Large Size**: Rotary encoders typically cost between $100 to $140, far more expensive than sensors like accelerometers, which range from $15 to $40. The rotary encoder's precision-machined slotted disk and optical detection system also make it bulky, complicating its integration into educational robot blocks.

(ii) **Heavy Shaft:** These encoders are usually built into motor units, and the heavy output shaft requires strong torque to rotate, making it difficult to use in educational settings.

(iii) **Difficulty of Reading Measurements:** Incremental rotary encoders, while cheaper than absolute encoders, present difficulties for novice users. They rely on pulse output signals to detect rotation angle and direction, which can be hard to interpret.

Addressing these challenges is essential to make rotary encoders more practical and accessible for educational purposes, particularly in environments where simplicity and ease of use are paramount.

1.4 Research Objective

This study aims to overcome the aforementioned challenges by introducing a non-contact magnetic rotary encoder into robot education kits. This approach seeks to establish a precise and reliable sensor system that can be easily utilized by beginners. By doing so, it aims to enhance learning outcomes in educational settings by providing students with more accessible tools for understanding and applying key concepts in mechatronics and control engineering.

2. Development of Rotary Encoder System for Robot Educational Kits

2.1 Selection of the Optimal Rotary Encoder

The AS5048B magnetic rotary encoder, manufactured by ams, was selected as the optimal encoder for application in robot education kits. The selection was based on its features and capabilities that meet the desired criteria for educational use. Table 1 provides a comparative overview of commonly used rotary encoders in educational literature and technical references, highlighting the advantages of the AS5048B. This comparison supports the suitability of the AS5048B for addressing the unique requirements of educational environments, including cost-effectiveness, ease of integration, and performance in dynamic scenarios.

Table 1. Comparison of Rotary Encoders for Educational Robot Kits.

Model Number	Manufacturer	Accuracy [deg.] [Count/Rot.]	Type / Interface	Price	Size	Key Features
M38H12-F-(1000)BZ5F2	Phidgets	1000 CPR (0.36 [degree])	Incremental / 2 signals (A, B)	Approx. $50	φ38.7 x 45mm, 180g	High-precision position detection
E6B2-CWZ6C	Omron	1000 CPR (0.36 [degree])	Incremental / 3 signals (A, B, Z)	Approx. $150	φ40 x 39mm, 100g	Widely used for educational robots
38S series	Nemicon	100-4096 CPR (3.6-0.088 [deg.])	Incremental / 3signals (A, B, Z)	Approx. $120-$150	φ38 x 35mm, 120g	Reliable product for position control
GlideWheel-M / -AS	Mindsensors.com	0.5 [degree]	Absolute / I2C digital	Approx. $50-$100	Approx. 30mm x 40mm x t5	Designed for LEGO EV3
AS5048B	**ams-OSRAM AG**	**0.0129 [degree] (14 bit / Rot.)**	**Absolute / I2C & PWM analog**	**$8-$10**	**5mm x 6.4mm (TSSOP)**	**Magnetic & Contactless**

1. **High Accuracy**: While the typical angular measurement accuracy of general rotary

encoders is approximately 0.36 degrees, the AS5048B achieves a significantly higher precision of 0.0129 degrees (14-bit resolution per rotation).

2. **Convenient Interface**: Rotary encoders are generally categorized as either incremental or absolute encoders. Incremental encoders are commonly used due to their simpler structure and fewer cable requirements. They typically utilize A, B phase signals, or A, B, Z signals including a reference position. A, B phase signals allow detection of rotation direction based on phase shifts and speed through pulse count rates. However, systems must maintain a memory of the current angle and ensure accurate updates for irregular pulse inputs, complicating implementation compared to other sensors. The AS5048B addresses these challenges with its integrated I2C serial interface, enabling direct angle measurement through high-speed serial communication with minimal cabling. While the I2C interface offers convenience, advanced configuration is required to avoid address conflicts when used alongside other I2C devices. To simplify integration into robot education kits, the AS5048B is designed to function like an analog sensor. In the proposed configuration, it connects to computers using just two wires (signal and ground), allowing direct measurement of absolute angles.
3. **Cost-Effectiveness**: Conventional incremental rotary encoders typically cost $100–$140, with lower-cost models priced around $50. In contrast, the AS5048B is highly affordable at $8–$10, making it an economically attractive option with excellent availability.
4. **Compact and Lightweight Design**: General rotary encoders rely on precision slotted disks attached to a shaft, combined with optical measurement systems. These designs typically measure approximately 40mm in diameter and 40mm in length, making them unsuitable for block-type robot kits where the sensor size exceeds the block dimensions. The AS5048B, with its TSSOP surface-mount package (5mm x 6.4mm), provides a compact and lightweight solution.
5. **Low Torque Requirement and Minimal Impact on Measured Systems**: Rotary encoders require minimal torque for angle and angular velocity measurements, reducing their impact on the measured system. Conventional encoders achieve this through high-precision and rigidly mounted rotating shafts, contributing to their large size and high cost. The AS5048B resolves these issues by employing a non-contact magnetic measurement system that detects rotation angles and velocities based on changes in the magnetic field, eliminating the need for heavy and rigid mechanical components.

2.2 Design of a Low-Pass Filter for Analog Signal Generation

As described in the previous section, this study adapts the AS5048B to function as an analog sensor, commonly used in robot education kits. The PWM monitoring signal provided by the AS5048B was utilized to achieve this functionality.

As shown in Figure 1, a simple RC low-pass filter was designed to convert the PWM signal into an analog signal. The low-pass filter smooths the PWM signal by attenuating high-frequency components, resulting in a steady voltage level corresponding to the duty cycle of the PWM signal. This allows the AS5048B to emulate the behavior of traditional analog sensors, enabling seamless integration into existing systems that rely on analog signal inputs.

Further details on the filter design, including the selection of resistor and capacitor values to optimize performance, are discussed in subsequent sections. This approach ensures compatibility with robot education kits while maintaining the precision and reliability of the AS5048B.

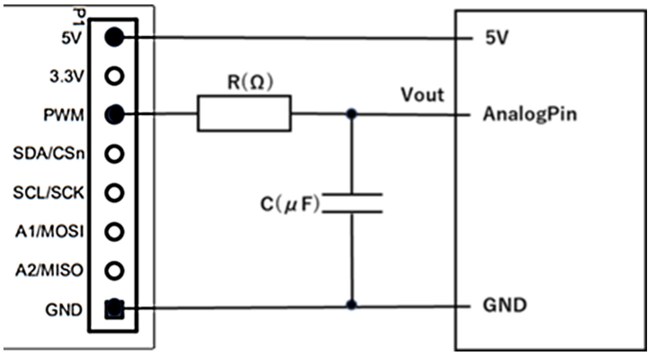
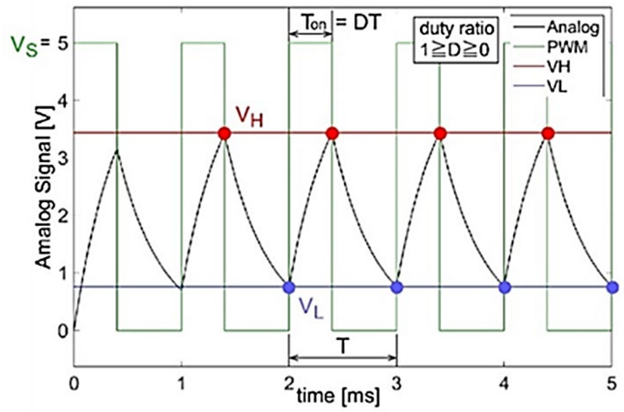


Fig. 1 Low pass filter for converting PWM signal to analog signal.

The capacitor in this low-pass filter charges and discharges according to the PWM signal, as shown in Fig. 2. The black line in the figure represents the output V_{out} of the low-pass filter. The maximum and minimum voltages of V_{out} are denoted as V_H and V_L, respectively. The time constant of the low-pass filter is optimized to minimize the difference between V_H and V_L, thereby reducing variability when reading values from the analog pin.

$$V_{\mathrm{out}}(t) = \begin{cases} (V_s - V_0)\left(1 - e^{-\frac{t}{RC}}\right) + V_0 & 0 \le t < DT \\ \left\{(V_s - V_0)\left(1 - e^{-\frac{DT}{RC}}\right) + V_0\right\} e^{-\frac{t-DT}{RC}} & DT \le t < T \end{cases} \qquad \text{Eq. 1}$$

V_{out} is expressed by Equation 1.



Key Parameters and Definitions

- V_H: Voltage at the end of the positive pulse.
- V_L: Voltage at the end of the negative pulse.
- V_S: Amplitude of the pulse ($V_S = 5\,\mathrm{V}$).
- T: Period of the PWM signal ($T = 1\,\mathrm{ms}$).
- D: Duty cycle of the PWM signal ($0 \leq D \leq 1$).
- T_{on}: Width of the positive pulse ($T_{\mathrm{on}} = D \cdot T$).
- V_{out}: Voltage of the filtered PWM signal.

Fig. 2 Charge / discharge characteristics of lowpass filter output.

A smaller time constant reduces the difference between V_H and V_L, resulting in less variability. However, it also decreases the ability to track rapid changes in angle. To ensure responsiveness to fast angular changes, the time constant was set to 10 ms by selecting a resistor R of 100 kΩ and a capacitor C of 0.1 μF.

$$V_H = \left(\frac{1 - e^{-\frac{DT}{RC}}}{1 - e^{-\frac{T}{RC}}} \right) V_S$$

$$V_L = \left(\frac{1 - e^{\frac{DT}{RC}}}{1 - e^{\frac{T}{RC}}} \right) V_S \qquad \text{Eq. 2}$$

V_H and V_L are determined using the above equations, showing that they depend on the PWM duty ratio D. The average value of V_H and V_L corresponds to the voltage representing the detected angle. The relationship between the duty ratio D and the voltage is shown in Fig. 3, with V_H and V_L indicated as error bars. The maximum difference between V_H and V_L occurs when the duty ratio is 50%, resulting in a deviation of ±62.5 mV. This corresponds to an estimated angular measurement error of approximately ±4.5 degrees.

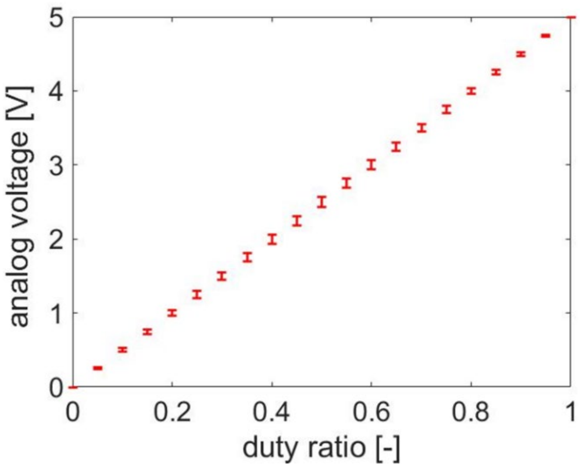


Fig. 3　Measured analog voltage errors of the V_{out} (Analog).

3. Sensor Unit Implementation and Evaluation

3.1　Implementation of the Rotary Encoder as an ArTec Robo Sensor Unit

The rotary encoder was implemented as one of the analog sensor units for “ArTec Robo”, a robot education kit developed by ArTec. The design schematic and the prototype appearance are shown in Fig. 4. This implementation enables seamless integration of the rotary encoder into the existing ecosystem of ArTec Robo, enhancing its functionality and educational applicability.

The observation results of the output from the implemented sensor module are shown in Fig. 5. The measured values closely matched the calculated values, confirming the accuracy of the implementation.

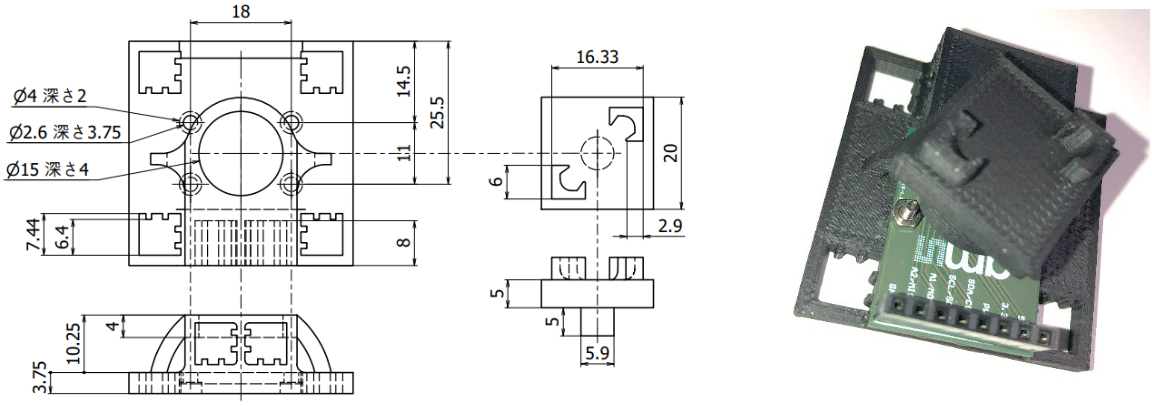


Fig. 4　Mechanical design for AS5048B as a general analog sensor unit for “ArTec Robo”.

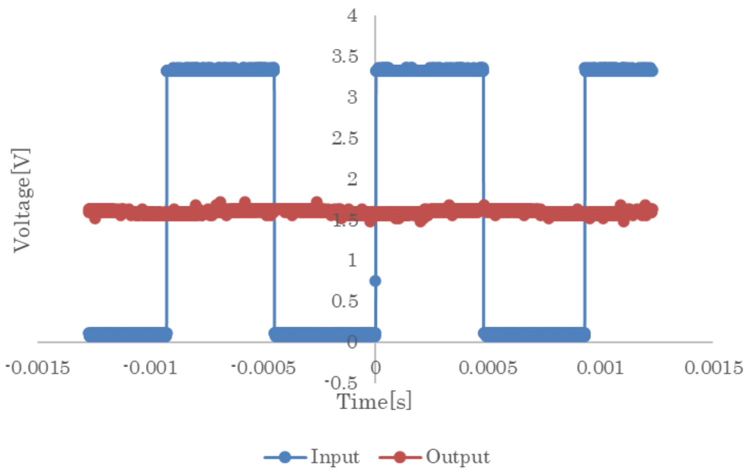


Fig. 5 PWM output of AS5048B (Blue: Input) and actual output signal of the lowpass filter (Red: Output).

3.2 Application and Evaluation in an Inverted Pendulum System

The proposed AS5048B rotary encoder module has been implemented in an inverted pendulum robot. The module is used to estimate the robot's angle and angular velocity, enabling stabilization control through state feedback using an optimal regulator.

Figure 6 shows examples of configurations for the inverted pendulum system. Figure 6a) illustrates the incremental type. The encoder itself is relatively inexpensive, but its output consists of two phase signals containing information on the rotation direction and rotational angular velocity. Therefore, the computer needs to process these phase signals in real-time to calculate the current angle. Figure 6b) shows the absolute type. In this case, the signal directly provides the angle through high-speed digital communication. However, the hardware is very expensive, and the computer requires an interface library to handle high-speed serial communication. Figure 6c) depicts a configuration using an IMU unit (gyroscope and accelerometer). Recently, IMUs have become very compact and affordable. However, since the angle is estimated by integrating the angular velocity, the error accumulates over time. Figure 6d) is an example of the proposed system configuration. The computer receives the angle directly through a conventional analog input for sensors, resulting in a very simple setup.

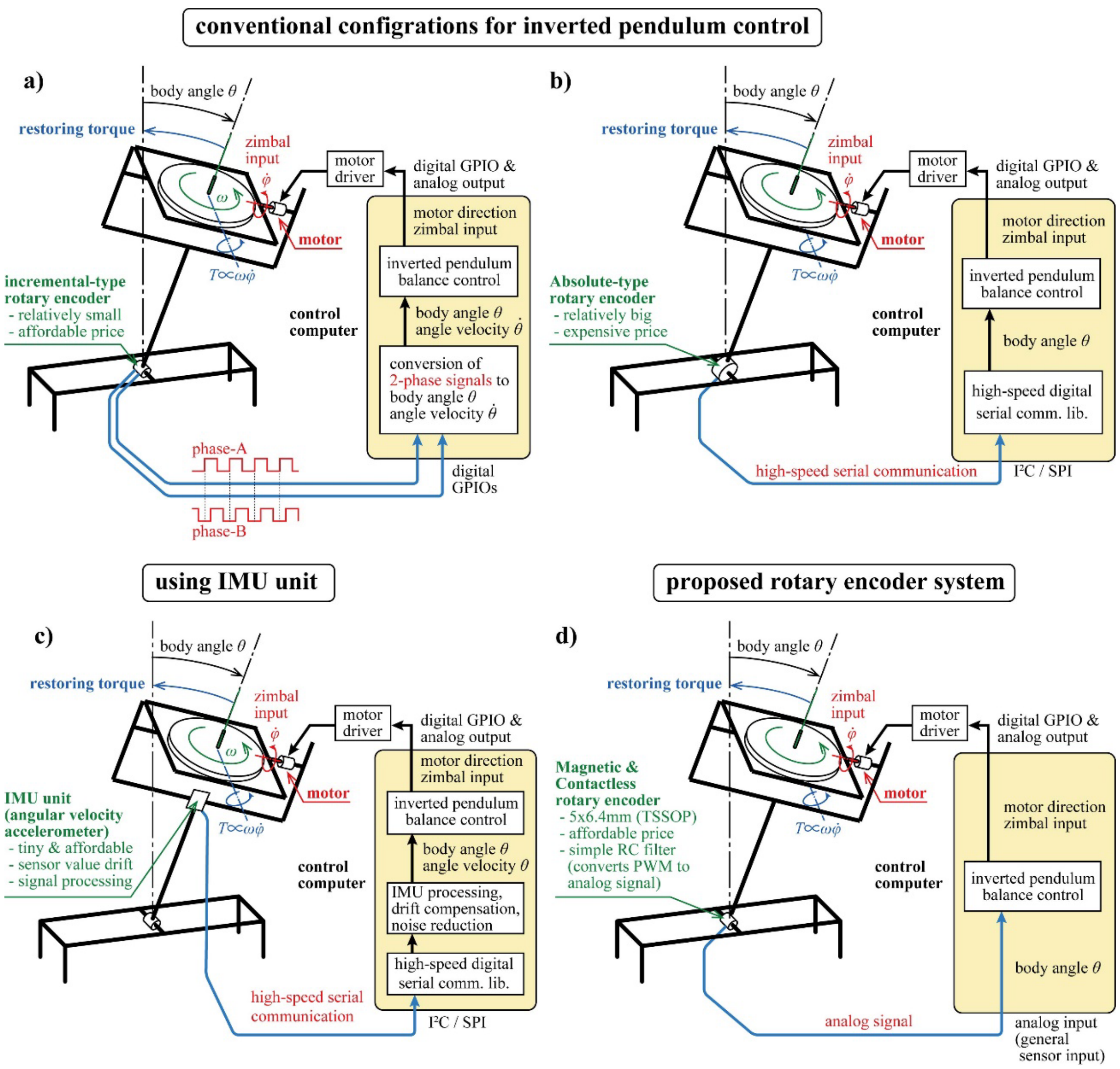


Fig. 6 Configurations of inverted pendulum system; a) and b) using conventional encoders, c) IMU unit and d) proposed rotary encoder.

Figure 7 shows the 3D simulation using (Simscape/Simulink) and the physical prototype.**

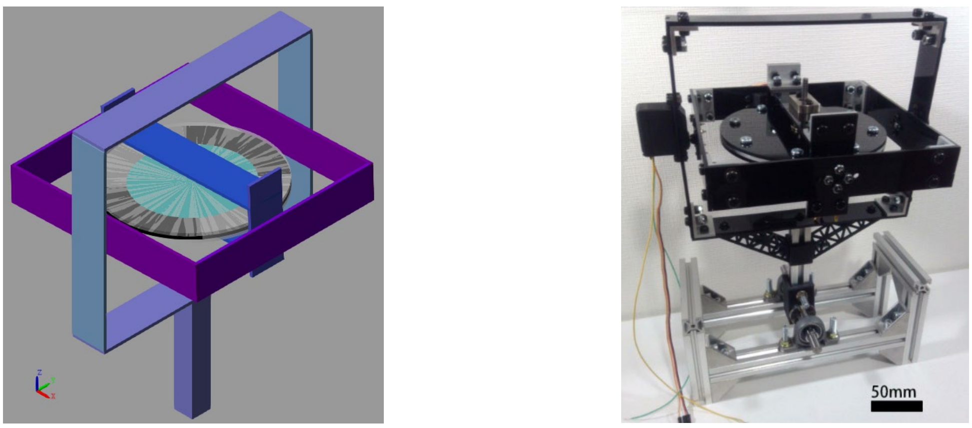


Fig. 7 Left: Simulation (Simscape/Simulink) and Right: actual prototype of inverted pendulum system using CMG.

4. Conclusion

This study developed and implemented a novel rotary encoder system using the AS5048B non-contact magnetic encoder for educational robotics applications. The following key findings and contributions were achieved:

1. **Cost-Effective and Compact Solution**: The AS5048B was chosen for its affordability, compact size, and high resolution. At only $8–$10, the encoder provides a cost-effective alternative to conventional rotary encoders while maintaining precision and reliability.
2. **Integration into Educational Kits**: The encoder was successfully adapted as an analog sensor unit for the ArTec Robo educational kit, demonstrating seamless integration into existing systems. This adaptation allows beginner-friendly access to high-precision angle measurement with minimal setup.
3. **Analog Signal Generation**: By designing and optimizing a low-pass filter, the PWM output of the AS5048B was converted into a stable analog signal. The resulting system demonstrated excellent agreement between calculated and measured values, confirming its reliability.
4. **Application to Control Systems**: The encoder module was implemented in an inverted pendulum robot to estimate angles and angular velocities, enabling stabilization through optimal regulator control. Furthermore, the module was used to identify critical parameters, such as the viscous damping coefficient, through experimental measurements.

Acknowledgement

This research is supported by JSPS Research Grants 24K06133 and the 2024 SIT's Grant for Educational Reform and Research Activity.

References

[1] R. Rütters, M. Bragard and S. Dolls, "The Inverted Rotary Pendulum: Facilitating Practical Teaching in Advanced Control Engineering," 2024 IEEE Global Engineering Education Conference (EDUCON), Kos Island, Greece, 2024, pp. 1-5, doi: 10.1109/EDUCON60312.2024.10578937.

[2] X. Jordens, R. Wilmart, E. Garone, M. Kinnaert and L. Catoire, "A Project-Based Learning Approach for Building an Affordable Control Teaching Lab: The Centrifugal Ring Positioner", in IEEE Access, vol. 10, pp. 4907-4918, 2022.

[3] Jones, J. P., & McArthur, C. W., & Young, T. A. (2011, June), The VU-LEGO Real Time Target: Taking Student Designs to Implementation Paper presented at 2011 ASEE Annual Conference & Exposition, Vancouver, BC. 10.18260/1-2--18559.

[4] Muldoon, J., & Phamduy, P. T., & Le Grand, R., & Kapila, V., & Iskander, M. G. (2013,

June), Connecting Cognitive Domains of Bloom's Taxonomy and Robotics to Promote Learning in K-12 Environment Paper presented at 2013 ASEE Annual Conference & Exposition, Atlanta, Georgia. 10.18260/1-2--19343.

[5] Nagchaudhuri, A. (2011, June), Real-time Control Implementation of Simple Mechatronic Devices Using MATLAB/Simulink/RTW Platform Paper presented at 2011 ASEE Annual Conference & Exposition, Vancouver, BC. 10.18260/1-2--18409.

[6] Turner, M., & Webster, R., & Reynolds, D., & Cooley, T., & McCart , A., & Dues, J. F. (2016, June), Purdue Mission to Mars: Recruiting High School Students to a Polytechnic College Paper presented at 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana. 10.18260/p.26017.

[7] Miao, L., & Karim, T., & Hussain, T. S., & Li, C. (2021, July), TNT Board: An Interactive Electronic Board Game Paper presented at 2021 ASEE Virtual Annual Conference Content Access, Virtual Conference. 10.18260/1-2--37911.