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STEMbot: An open source-based robotic kit as a middle school STEM education interest catalyst

***Abstract**. STEM education has been formally introduced in order to foster student interest towards science and technology fields. Different approaches, strategies and tools have been used in order to implement an integrative STEM education at difference levels of education. Robot is one of the widely used tools to implement an integrative STEM education where the STEM components can be integrated and implemented using a single platform. However, the commercially available robotic platforms are mostly proprietary, high cost and has very restricted functions. In addition, the development of the proprietary robotic platforms and its activities are mostly not considering the content of the STEM related subjects in school. This study intends to develop a robotic kit (known as STEMbot) based on Mechatronics Design Process approach considering the STEM related course contents of the middle school in Malaysia using on open-source development tools. The findings demonstrate that the proposed STEMbot robotic kit has a positive impact in realizing an integrative STEM education as shown by the positive feedbacks from the schools' teachers.*

***Streszczenie.** Edukacja STEM została formalnie wprowadzona, aby zwiększyć zainteresowanie uczniów naukami ścisłymi i technologią. Aby wdrożyć integracyjną edukację STEM na różnych poziomach edukacji, zastosowano różne podejścia, strategie i narzędzia. Robot jest jednym z powszechnie stosowanych narzędzi do realizacji integracyjnej edukacji STEM, w której komponenty STEM można integrować i wdrażać przy użyciu jednej platformy. Jednakże dostępne na rynku platformy robotyczne są w większości zastrzeżone, drogie i mają bardzo ograniczone funkcje. Ponadto rozwój własnych platform robotycznych i ich działania w większości nie uwzględniają treści przedmiotów związanych ze STEM w szkole. Celem tego badania jest opracowanie zestawu robotycznego (znanego jako STEMbot) opartego na podejściu Mechatronics Design Process, uwzględniającym treści zajęć związanych ze STEM w gimnazjum w Malezji przy użyciu narzędzi programistycznych typu open source. Odkrycia pokazują, że proponowany zestaw robota STEMbot ma pozytywny wpływ na realizację integracyjnej edukacji STEM, o czym świadczą pozytywne opinie nauczycieli w szkołach. (**STEMbot: Zestaw do budowy robota oparty na oprogramowaniu typu open source jako katalizator zainteresowania edukacją STEM w szkole średniej**)*

Keywords: robot, STEM education, open-source, middle school.
Słowa kluczowe: robot, edukacja STEM, otwarte źródło, Gimnazjum.

Introduction

Every nation strives to become a developed nation by making preparations and persistent efforts to guarantee that the goal can be accomplished. Among the nations that aim to achieve developed status is Malaysia. Fields related to Science, Technology, Engineering, and Mathematics (STEM) are among the most crucial aspect of science and technology for a nation to be recognised as a developed nation. In many rich and developing nations alike, increasing the proportion of graduates in STEM-related disciplines has emerged as a national goal. Creating STEM-literate students who can recognise problems, comprehend them, and apply and integrate STEM-related principles into solutions is the aim of STEM education. Along with being creative, ingenious, and innovative, STEM-literate students should also possess 21st-century skills and branches of knowledge related to the Industrial Revolution 4.0.

The government of Malaysia has established a goal to achieve a ratio of 60:40 of students who register in STEM-related courses to non-STEM-related courses [1]. Nevertheless, the number of students enrolling in the STEM stream has been declining over the years, despite its significance and rising demand in various work sectors. The data on Form 4 and Form 5 students' enrolment in the STEM stream in 2012 and 2017 showed a declining trend, with the percentiles being 48.15% and 45.74%, respectively [2].

Numerous factors, including a lack of enthusiasm or drive, inadequate curriculum, time and financial constraints, and poor facilities, have been linked to this tendency [3-5]. The Malaysian government has launched a variety of measures to address these issues and boost enrolment in the STEM stream. According to Nordin [6], the government of Malaysia has launched three significant initiatives to improve STEM education in the country:

- Stimulate students' interest in STEM through formal and informal approaches to learning,
- Sharpen teachers' knowledge and skills in teaching STEM-related subjects through continuous professional development programs and
- Increase awareness and acculturation in STEM among students, teachers, and the community through STEM programs.

Beginning in kindergarten and continuing through postsecondary education, there has been a push to encourage kids to enrol in STEM-related disciplines [7]. Nonetheless, since high school is when students choose their educational path for their future careers, their interest in STEM subjects should take precedence. According to a study by Malik, et al. [8] parents' backgrounds had an impact on their children's degree of interest in STEM. Parents with lower educational attainment are presumably less likely to encourage their children to pursue studies in STEM fields because they haven't had as much exposure. Furthermore, it has been determined that a primary cause of students' disinterest in enrolling in STEM programmes or even switching from STEM to non-STEM during their undergraduate studies is a lack of interest [9]. Therefore, a drastic measure is required to draw students into the STEM stream and ensure that Malaysia can develop, supply, and meet the demand for highly trained human capital in STEM-related professions.

Integrative and isolated STEM are the two approaches to implementing STEM education [10]. However, as STEM does not address worker needs or real-world issues, it should not be applied in an isolationist manner [11]. As a result, integrative STEM—which integrates STEM content, problem-centred learning, inquiry-based learning, design-based learning, and cooperative learning—has been recognised as an emerging strategy to draw children towards STEM [12]. Project-based inquiry learning is the method used in integrative STEM implementation [13]. One of the main components used in the development and application of Malaysia's Secondary School Standard Curriculum (KSSM) is the integrated STEM [14].

It has been demonstrated that students who participate in hands-on projects will be more interested in STEM [15] and that indirect learning can have a favourable impact on the development of interest in STEM [16]. One of the indirect learning strategies is hands-on robotics, which is included in STEM education modules. Prior research has demonstrated that when students handle robotic systems firsthand, regardless of gender, they become positively interested in STEM education [17-19]. As a result, robots have been applied for various scopes and various levels of education [20, 21].

Robots can support students in acquiring a deep conceptual understanding, competencies, problem-solving and critical thinking through creating and learning [22]. Additionally, it also improves the behavioural, social, scientific, cognitive, and intellectual aptitudes of the students [23]. Moreover, robot promotes students' computational thinking skills [24]. Robots have therefore been used in a variety of contexts and educational levels.

Incorporate dynamic STEM activities centred around robotics into classrooms to encourage students to take an active role in their education by assigning them a variety of robot-related assignments is an example [25]. Students learn about STEM subjects and acquire soft skills like problem-solving and teamwork via robotics [26]. Students' critical thinking skills can be improved by robot cooperative learning [27].

The programme should be interactive, expandable, conceptual, hands-on, economical, in line with the syllabus, and useful outside of the classroom [28]. Currently, a single robot with fixed components or a non-modular architecture is still the main idea of execution of robotic-based STEM education [18]. The concept of inexpensive, cooperative robots with a restricted range of senses, and hence a restricted range of operations or duties [29]. In contrast to the anticipated goals of low cost, attractiveness, simplicity, and open source, the design is not modular, has a specific purpose, requires software installation, and is pricey [30].

Furthermore, it has been demonstrated that multitasking robots may spark students' interest in STEM subjects through programmes like modular design, where students can integrate robots to complete certain tasks [31] and modular design where students can perform robot integration for a selected task [32]. Students will be able to investigate and apply broader STEM-related information through problem-based learning with the help of multitasking robotic systems [33]. For multitasking purposes, different sensors and actuators are needed for a specific task [34] such as an infrared sensor for object detection [35], a light sensor for light detection [27], etc. Consequently, creating a detachable module for a robotic system can expand robot functions, encourage students' creativity through problem-based learning, and intensify their interest in STEM education [36].

As for now, the integration of robots in educational environments is deemed too restricted, costly, and possessing restricted capabilities (i.e., a solitary motor and sensor type) [37]. One of the best resources for teaching STEM that shows how all of the STEM fields—science, technology, engineering, and math—are integrated is the robot. Students' interest in pursuing a STEM-based education can be sparked by a robotic system, with affordability and educational design taken into consideration. However, since a robotic system's relatively limited function exposes pupils to very little STEM, it will not be able to draw students to the STEM stream. If robots are designed using blocks or other building blocks, they can aid with computational thinking [38]. Therefore, a robotic system with an extensive educational module that offers a broader understanding of STEM components is required.

A robotic kit that takes into account open-source development is suggested in this study. The ensuing sections will delve more into the specifics of the procedure. The remainder of this essay is structured as follows: Methodology, Result, Discussion and Conclusion.

Methodology

The robot is designed and developed using a mechatronics design process, as suggested by [39], in order to meet the study's goal. The overall design process is based on the two primary phases of mechatronic system design, as depicted in Fig. 1 which consists of system design and system integration. System design is the first step in the process, which is followed by the detailed design of the subsystem and the realisation and testing of each component. Robot components are combined into subsystems during the system integration stage, and the subsystems are then integrated to form a whole robotic system. When the process was complete and the finished product was ready for use, a comprehensive functionality and usability test was carried out.

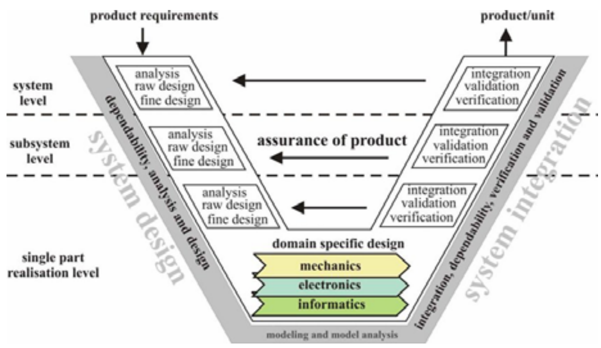

Fig.1. An example of the figure inserted into the text [39]

Requirements Identification

In this study, a mobile robot platform is developed considering the following requirements:

- Low-cost: The used components (sensors, actuators, body frame materials, etc.) are the off-the-shelf low-cost components.
- Open source: The tool for operating the robot is designed and developed based on open-source tools where the proprietary design is avoided.
- Syllabus aligned: Robot task development was derived from STEM-related course syllabuses. The middle school curricula were taken into consideration in this study. In Fig. 2, the extraction procedure is displayed.
- Flexible: Depending on the needs, more sensors or actuators can be added. Any component without any proprietary features can be included in these additional components.
- Modular: The robot's parts are categorised according to a color-coded module that helps distinguish between input, output, actuators, and sensors. Table 1 contains a list of the modules that correspond to the course syllabus.
- Simple: The designed should be easy to assemble and program suitable to the level of knowledge of the target user.

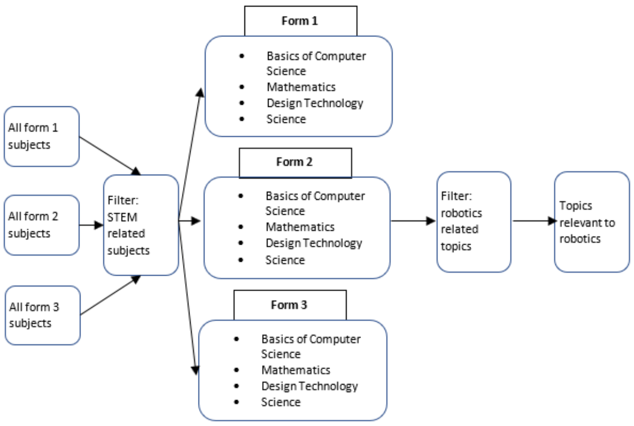

Fig.2. Extraction of relevant topics from STEM related subjects

Table 1. The parameters of the sensor

Module	Related topics	Function
Programming	Computational thinking, Data representation, Algorithm development, Linear equations, Linear inequalities, Lines and angles, Pythagoras Theorem	Introduce programming idea block programming implementation of mathematics concepts
Light detection	Properties of light	Detect the location of light source by using light sensors
Sound generation	Sound wave	Generate sound to indicate certain situations with different tones
Temperature measurement	Heat	Measure the surrounding temperature and display the value to LCD
Mobility	Circles, Coordinates, Physical quantities and their units, Trigonometric ratios, Straight lines, Forces and Motion	Explain and demonstrate how robots move from one location to another
Communication	Basic concepts of computational thinking, Data representation Algorithm development, Command code	Explain how robot receive instructions wirelessly or wired by means of algorithm and instruction code.
Line following module	Linear equations, Coordinates, Straight lines, velocity and acceleration	Demonstrate function of robot according to desired straight path connecting coordinates at a specific speed
Distance measurement	Sound waves, speed	Explain how sound wave is used for the purposes of distance measurement
Power supply	Electricity and magnetism, Electricity generation, Energy and power	Voltage, current, resistance and power concept

System Design

The overall system design of the robot is shown in Fig. 3 through Fig. 5. Each module is designed based on a different colour scheme. This robot is developed from off-the-shelf components. The design was initially performed using proprietary software but for educational purposes, the generated file of the independent components can be reopened in any equivalent software where students can view, manipulate and redesign the component if necessary. The size of the STEMbot is relatively small (i.e., 158 mm x 120 mm) as shown in Fig.5.

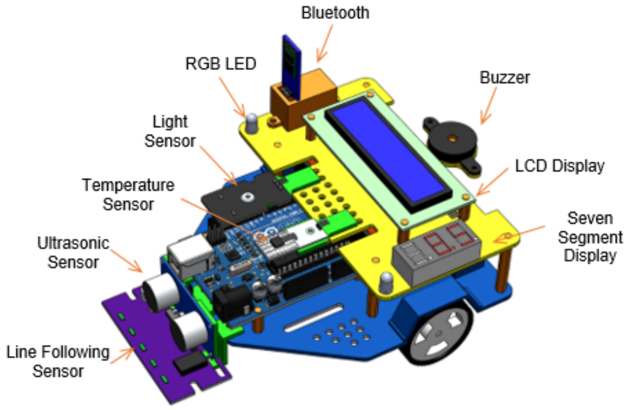

Fig.3. Isometric view of the robot system design

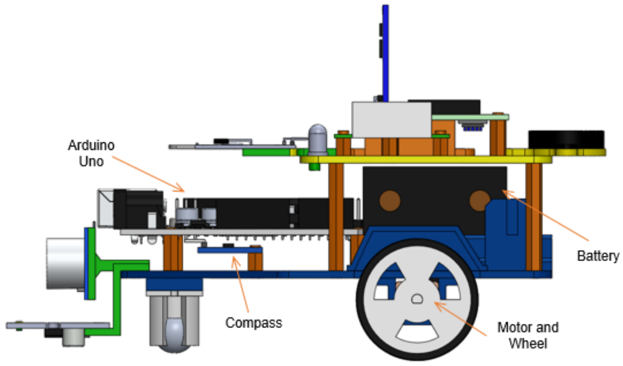

Fig.4. Side view of the robot system design

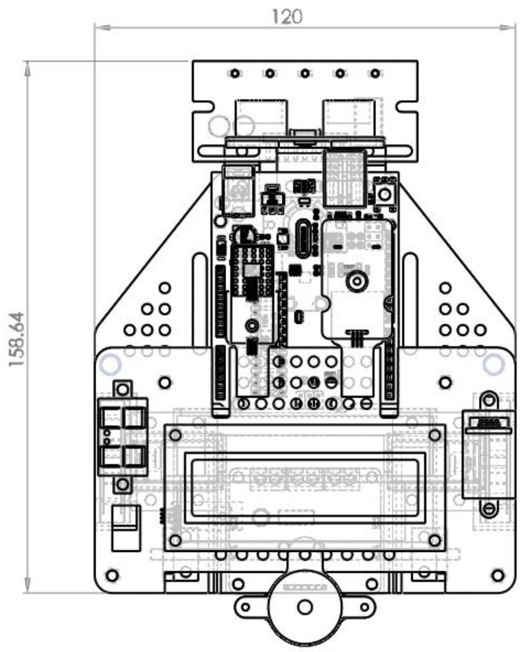

Fig.5. Dimension of STEMbot in mm

The subsystems (see Fig. 1) of the STEMbot represent the required module extracted from the related courses and topics as shown in Fig. 2. The subsystems of the robots consist of the following modules:

- Programming Module

Consists of an Arduino Uno microcontroller and Ardublockly as a programming software. The coding of the robot is based on block programming instead of text programming. In this module, students will learn about algorithm development and programming principles to complete the given task.

- Light detection module
Consists of a low-cost light sensor. Students can learn how the properties of light through robotic tasks such as searching for a light source.
- Sound generation module
A low-cost buzzer is used to generate sounds of different tones concerning certain robotic activities. Students will learn how a buzzer generate sound.
- Temperature measurement module
Has a low-cost temperature sensor to detect the temperature of the environment as the robot explores the environment.
- Mobility module
Consists of two wheels, a caster wheel, a pair of DC motors, a motor driver and a compass. Robot navigation can be controlled manually using mobile apps or using autonomous mode of operation.
- Communication module
Consists of a low-cost Bluetooth module and an open-source app for controlling the robot. This Bluetooth module will allow communication with the smartphone to control the robot.
- Line following module
Consists of a set of a low-cost line following sensors.
- Distance measurement module
Consists of an ultrasonic sensor. In this module, students can learn the concept of velocity of sound and the calculation of distance from the speed of sound.
- Power supply module
Consists of two Li-Ion batteries and a seven-segment display. The seven-segment display is used to display the total voltage value of the two batteries. In this case, student will learn the concept of voltage. A rocker switch is used to turn on or turn off the robot.

For programming the STEMbot, an open-source ArduBlock block-based programming platform is selected since it can be used both online and offline. In addition, the possibility of adding libraries makes it flexible and easier to interface with external inputs or outputs. Block-based coding is chosen since it is more suitable for middle school students compared to text-based coding. An example of coding for robot movement in a straight line while reading distance from an object is shown in Fig. 6.

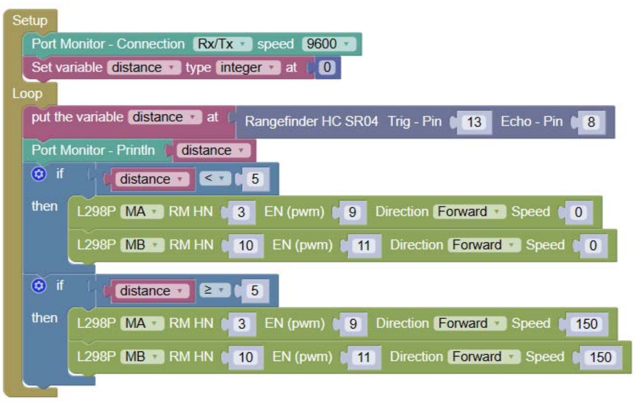

Fig.6. Example of STEMbot coding using ArduBlock

For starting and stopping the robot, a simple mobile application based on the open-source tool (i.e., MIT Apps Inventor) is developed as shown in Fig.7. This app can also be used to manually control STEMbot using the specific buttons. Even though the quality of the apps is not as good as the apps developed by using the paid platform, it sufficiently serves the purpose without incurring any additional development cost. Additionally, since the coding of the apps is based on block coding, a fast development process is possible. In this case, the application can be deployed on a smartphone or tablet and the communication with STEMbot can be established easily by using Bluetooth wireless communication. Part of the coding used in the development of the apps for controlling the STEMbot is shown in Fig.8.

Fig.7. Apps for controlling the STEMbot develop using MIT Apps Inventor

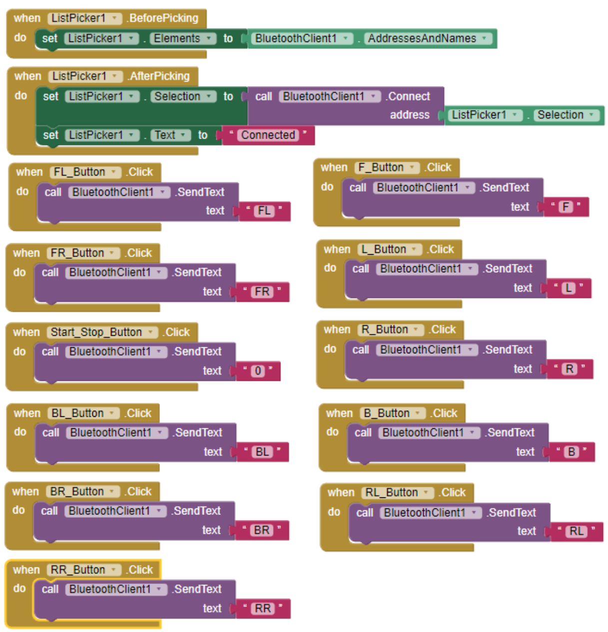

Fig.8. Part of apps coding for controlling the STEMbot

For robot frame and mechanical components design, Solidwork is used and all components were saved as a standard 3D printing file (i.e., .STL files) for the 3D printing and learning process by the students. The files can be easily reopened in Tinkercad 3D Design or any other open-source 3D modelling platform that supports the STL file in case students are required to understand the design as part of the planned STEM activities.

System Integration

A complete STEMbot prototype after the integration is shown in Fig. 9. In the developed robot, the blue colour base represents the chassis of the robot, the yellow base represents the output, the green base represents the input and the brown base represents the communication module. The bill of material for the STEMbot is listed in Table 2.

The body frame of the robot was fabricated using a 3D printer. With relatively low-cost material for printing purposes compared to acrylic or metals, the overall cost of the robot can be reduced and if necessary, it can be reprinted easily.

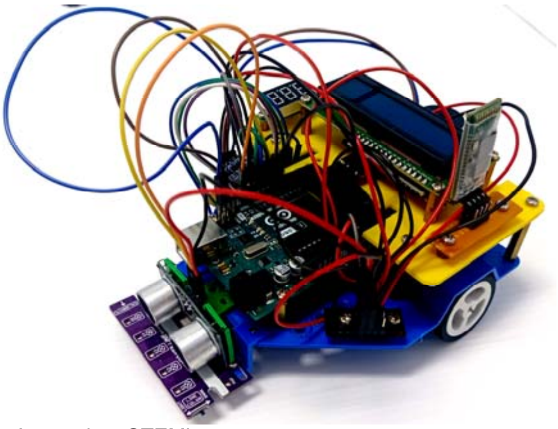

Fig.9. A complete STEMbot prototype

Table 2: Bill of materials for STEMbot

ITEM NO.	PART NAME	QTY.	Cost (USD)
1	Frame type 1	1	0.30
2	Wheel	2	2.00
3	Caster wheel	1	0.64
4	DC Motor	2	7.84
5	LCD display	1	3.92
6	PCB stand-15 mm	8	1.36
7	RGB led	2	0.42
8	DC motor driver	1	3.81
9	Battery holder	1	0.38
10	Bluetooth module	1	4.13
11	Light sensor	1	1.06
12	Temperature sensor	1	1.04
13	Motor bracket	2	0.10
14	Motor driver bracket	1	0.10
15	Battery	2	2.08
16	Arduino Uno	1	6.14
17	Wheel cover	2	0.10
18	Ultrasonic sensor	1	0.70
19	Ultrasonic sensor bracket	1	0.10
20	Line sensor bracket	2	0.15
21	Buzzer	1	0.32
22	Buzzer bracket	1	0.10
23	Bluetooth casing	1	0.15
24	PCB stand-30 mm	4	0.70
25	Frame type 2	1	0.90
26	Sensor bracket	2	0.20
27	Compass	1	4.24
28	Battery enclosure	2	0.15
29	Battery stopper	1	0.10
30	Seven segment display	1	1.17
31	PCB stand-5 mm	4	0.70
32	Line sensor	1	4.24
TOTAL			49.34

Experimental Setup

To demonstrate how the STEMbot can be used for implementing STEM education, the tests shown in Table 3 related to several topics of the middle school syllabus were conducted. The test is relatively simple but it aligns with the knowledge the middle school students possess.

Table 3: Robot tests related to STEM syllabus

No	Test	Objective
1	Speed measurement	Determine the speed of the robot
2	Light detection	Navigate and locate the position of the light source
3	Line following	Follow a line
4	Obstacle detection	Measure obstacle distance and stop moving

In the speed measurement test, the robot will travel at a certain speed from one location to another. During this navigation process, the time taken will be measured for different Pulse Width Modulation (PWM) values which represent the percentage of speed where it can be calculated as (Note: PWM of 255 represents the maximum speed of the robot using Arduino Uno):

(1) $$v_{\%} = \frac{255 - PWM_s}{255} \times 100$$

where: PWM_s – set PWM value. In this case, the travelled distance is fixed at 1.0 m.

From the known distance and time, the actual speed of the robot in m/s can be calculated. Different speeds will be set during the experiment. From the STEM education perspective, students will learn about the concept of speed where speed can be calculated as:

(2) $$v = \frac{s}{t}$$

where: s – travelled distance, t – time. In this case, the travelled distance is fixed to 1.0 m.

For the light detection task, the robot will travel in a straight line and stop when the source light is detected. The position of the light source is fixed at one location and the starting position is 1.0 m away from the source. The intensity of light will be measured and recorded as a function of time.

(3) $$I = \frac{P}{A} = \frac{Power}{4\pi r^2}$$

where: P – power, A – area which is an area of a sphere. In this case, the travelled distance is fixed at 1.0 m. The robot moves in a straight line and stops when the set intensity is met.

For the line following test, the robot will follow a shape line as shown in Fig. 10 and the time taken to complete the task for a specific speed value will be recorded (in this case, speed is set at a PWM of 150). The reading of the compass sensor will be recorded during the process.

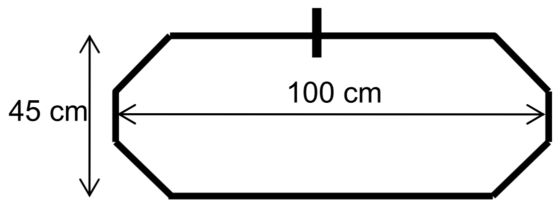

Fig.10. Infrared sensors reading during the line following task

For the controller design, a simple bang-bang controller was used instead of a more advanced controller for example PID, SMC, etc to match the level of understanding of middle school students [40]. This controller is closely relevant to the logical thinking of students compared to a more advanced controller. The used rules are shown in Table 4.

Table 4: Line following control rules

IR Line Sensor State					Motor Speed (PWM)		Movement
D1	D2	D3	D4	D5	L	R	
0	0	1	0	0	250	250	Forward
0	1	0	0	0	50	250	Turn left
1	0	0	0	0	0	250	Sharp left
0	0	0	1	0	250	50	Turn right
0	0	0	0	1	250	0	Sharp right
1	1	1	1	1	0	0	Stop

During the obstacle detection task, the robot will move in a straight line and stop when an obstacle is detected at a distance of 5 cm. The values of distance were recorded. In this case, the ultrasonic sensor measured the distance based on the principle of speed of sound in the air given by

$$d = v\frac{t}{2} \quad (4)$$

where: v – speed of sound in air (~340 m/s), t – time taken for sound to rebound. In this test, the travelled distance is fixed at 1.0 m.

The demonstration of the product was performed to the pre-service teachers and middle school teachers and a survey was conducted to determine the usability of the product in conducting STEM teaching and learning practices. The total number of evaluators is 30 teachers who have at least several months of experience in the teaching and learning process.

Result and Discussion

Recap the objective of this study is to develop a reliable, practical and low-cost robotic kit to implement STEM education. Additionally, using open-tools tools for designing, developing and implementing will ensure that the activities can be conducted in a flexible interactive way. Moreover, developing activities related to and aligned with the course syllabus will allow students to learn and apply knowledge practically relevant to real-world problems.

Through the proposed robotic kit, the components of STEM can be implemented separately or in an integrated way. Examples of STEMbot activities relevant to course syllabuses are shown in Table 4.

Table 4: Example of STEM components and relevant robot task

Course	Topic	STEM	Robot Activity
Science	Nature of Light	S	Light intensity detection
Fundamentals of Computer Science	Algorithm development	T	Algorithm development for robot task
Design Technology	Pictorial Sketches	E	Viewing and editing sketch
Mathematics	Ratio number-Integer	M	Robot movement-forward and backward
Design Technology	Mechatronics System Design	S, T, E, M	Identifying robot components and its function for line following task

To study the design of the STEMbot, students can use the provided STL files to regenerate and edit the necessary parts using the open-source Tinkercad 3D Design application. Fig. 11 illustrates how this activity can be performed. In the school syllabus, this task is related to the pictorial sketches as part of the Design Technology course.

Among the easiest robotic tasks is a line-following task. Fig. 12 demonstrated a heading value during a line following task. From the figure, it can be seen that the heading of the robot is the same in the beginning indicating the robot moves in the same direction (following a straight path) and changes its heading direction as it follows the slope line as indicated in Fig. 12. Again, at the end of the movement, robot follows a straight (indicated by the constant heading) before stop (indicated by the constant heading at the end).

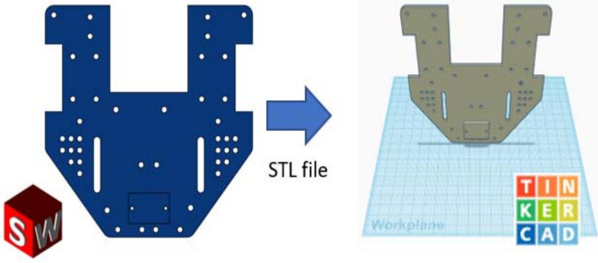

Fig. 11. Part of apps coding for controlling the STEMbot

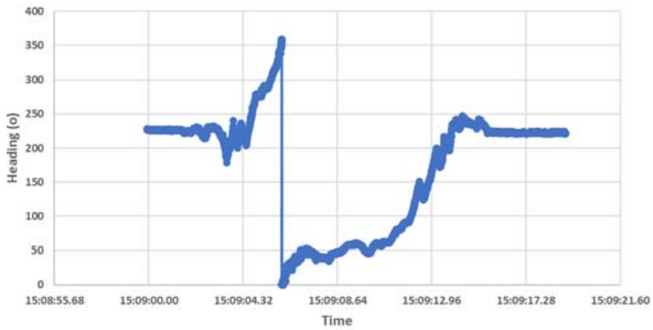

Fig.12. Heading versus real-time during a line following task

Through the line following task, the element of science can be adapted through the concept of line detection by the IR line sensor (i.e., radiation of infrared light). The technology concept can be related to how the programming of a microcontroller is used to perform the line-following task. This proses involves the use of a computer for programming microcontrollers. The engineering component can be related to the process of attaching the sensor and actuator at a suitable location for the line following purpose. The mathematic element can simply relate the concept of the direction of a robot with the direction measured by a compass.

The speed characteristic versus the PWM of the robot is shown in Fig. 13. Here, the practical implementation of speed calculation can be performed. In STEM activity, students will be able to determine and apply the concept of speed through the robot by simply adjust the PWM values.

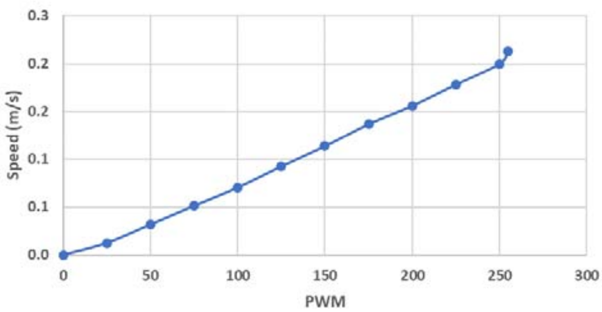

Fig. 13: Speed versus real-time measurement

The light intensity measurement can be used for understanding the characteristics of light. In this case, the proportionality of light intensity with distance can be analysed. The robot moves in a straight line while sampling the light intensity values. The robot initially the measured intensity of the background light and as it moves closer to the light source, the light intensity increases. The robot stopped moving when light intensity reached greater than 800 as indicated by the measured intensity values as shown in Fig. 14.

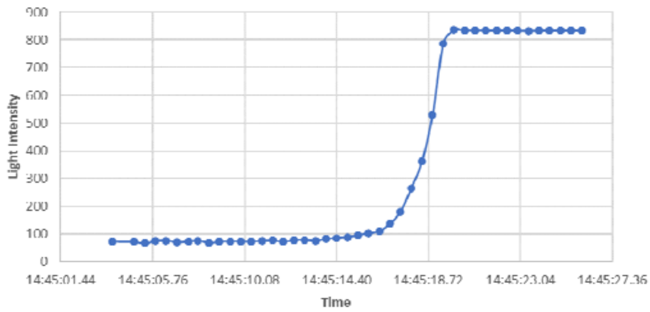

Fig. 14: Light intensity versus real-time measurement

In the distance measurement task, the robot moves in a straight line while sampling the measured distance (distance from the robot to the object). Before the robot moves, the measured distance is consistence and as it moves closer to the object, the measured distance gradually decreases. Once the robot stops moving about 5 cm from the object, the measured distance becomes constant as shown in Fig. 15.

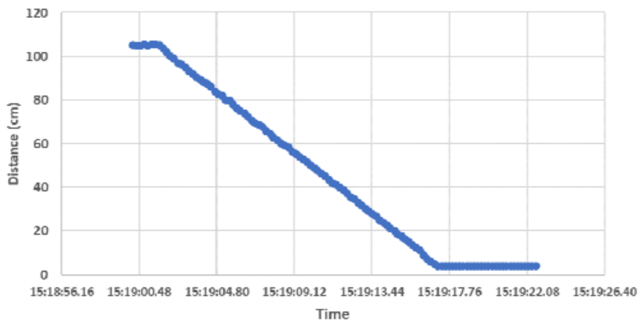

Fig. 15: Distance versus real-time measurement

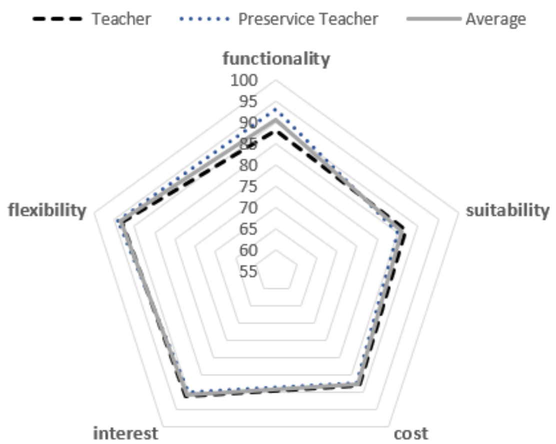

Fig. 16. Usability result of the STEMbot

To test the usability of the proposed STEMbot, a short survey has been conducted to evaluate its five important factors: functionality, suitability, cost, interest, and flexibility. The result of the survey is shown in Fig. 16. From the results, 90.5% out of 30 respondents agreed that the idea is interesting to attract students towards science and technology. In addition, 90.5% of respondents stated that the robot has full functionality in STEM education, especially in integrated STEM. In terms of the suitability of the robot for middle school students, 86.0% of them think the idea is suitable and relevant to the course syllabuses. The cost of the STEMbot is practically low since (below USD 50) it uses open-source development platforms as proven by the responses where 93.5% of the respondents agree that the course is relatively low compared to the proprietary robotic platform which usually costs hundreds of dollars. Thus, we can conclude that the STEMbot robotic kit meets the requirements as a tool for STEM education at the middle school especially, for Malaysia's educational system.

Conclusion and Recommendation

This paper discussed the design and development process of an open-source robotic kit for STEM education known as STEMbot. The design process follows a mechatronics design process which consists of two steps namely design and integration. The development and operation of the end product are based on open-source tools. The findings showed that the STEMbot kit can be used to implement integrative STEM by considering the course syllabus with relatively low cost but with flexibility in design activities. This finding is supported by the user usability test which proved that the STEMbot is useful for designing and implementing STEM education.

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