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Project Based Learning of Free-Falling Objects in Physics: Microcontroller-Based Multi-Sensor Test in Granular Flow Rate Measurement

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Abstract: The understanding of learning materials by students is the primary goal of education. However, this is not easily achieved by students. Teachers must make various innovations so that students can easily grasp the learning materials. Free-falling objects are one of the main topics in physics. Learning materials can be delivered through project-based activities in the classroom. Through class projects, empirical research can be conducted by both students and teachers. This article presents the tools and testing results related to the motion of granular materials as project-based learning. The flow rate of granular material in this project will illustrate the relationship between distance and time in free-fall motion. Therefore, this research designs and constructs a granular flow rate measurement system based on multiple sensors and a microcontroller to demonstrate the concept of free-falling objects through project-based learning. The method used is the design and construction of a device consisting of electronic and mechanical systems. The granular motion will be detected by the sensors. The main part of the electronic system consists of a microcontroller and five infrared sensors, which include five transmitters and five receivers. The mechanical system consists of a granular holding platform. Several types of granular materials are used for testing the flow rate measurement system. The lowest flow rate among the tested granular materials is around 70 grams/s for basil seeds, and the highest flow rate is for colorstone, with a flow rate of around 200 grams/s. The results also align with the basic physics concept of freefalling objects, which states that velocity increases as they approach the earth's surface due to the influence of gravity and distance. With the results obtained, this project-based learning device can be used to validate existing theoretical concepts.

Index Terms: project learning, flow rate, free fall object, granule, physics, sensors integration

1. Introduction

Various methods can be employed to deliver educational materials more effectively and deeper understanding. One of them is through research and project-based learning activities [1–4]. Direct student involvement in project-based learning activities will significantly enhance their understanding of course materials, making learning dynamic and fostering skill development [5, 6]. Moreover, with the rapid advancement of technology supporting the understanding of learning concepts [7, 8], the topic of free-fall motion in physics can be taught by building and testing a granular flow rate measurement device. This approach links classroom learning with laboratory testing equipment, which has not been previously connected. The relationship between time, distance, and velocity will be evident when this project is tested. The granular flow rate parameter is critical to study, especially in relation to basic physics concepts. Different studies have been conducted in an effort to study and acquire the appropriate characteristics of granules to be used as an industrial product, however, there has been no attempt to link them with classroom learning materials [9–13]. Computational observation of granular motion has been simulated through numerical modelling and similar methods to depict granular interaction and friction between granules that can lead to damage [14–16]. Researchers have also conducted research addressing the mathematical calculation of interaction forces on granules [16–18]. Many of the existing granular flow research projects are aimed at industrial products, whereas they should also be connected to basic theoretical concepts during the research process. This would allow them to be utilized in classroom learning.

The specific study of granular flow rate by Zhao et al. and Záhonyi et al. [19, 20] uses high-speed cameras to record the electrostatic reactions that happen when moving granular walls hit each other. Image processing and direct comparison of granular tracking results have also been conducted by Gollin et al. [21] to determine granular flow rates. Meanwhile, research on flow rates conducted by Jiang et al. [22] utilizes voltage sensors for the purpose of dispensing granular fertilizer on fields that can be automatically controlled. The specific study of granular flow rate by Zhao et al. and Záhonyi et al. [19, 20] uses high-speed cameras to record the electrostatic reactions that happen when moving granular walls hit each other. Meziane et al. [23] used sensors based on the pulse induction principle for detecting granular objects subjected to a rapidly changing electromagnetic field. The foundational study from the above research should be used as a project-based learning activity for students in the classroom, thereby helping students understand the material better.

The opportunity for utilizing sensors and microcontrollers in the measurement process of granular flow rates remains wide open, given the availability of various types of sensors and microcontrollers as the brains of automatic systems that can be developed [24]. However, in reality, granular flow rate measurements are still often manually conducted using stopwatches in some basic laboratories. On the other hand, innovative methods of delivering learning materials are needed to better motivate students. As mentioned at the beginning of this chapter, teaching materials and concepts through project-based learning (PBL) will enhance students' understanding and motivation to learn. As a result, this study develops a project-based learning and research approach that realistically illustrates the concept of free-fall motion in physics using a granular flow rate detection device. Currently, research is being conducted to develop a multi-sensor LDR-based system and microcontroller for measuring granular flow rates that can be utilized in pharmaceutical sciences and related fields. Sensors are arranged vertically to ensure that the granular flow rate will be the same regardless of where the measurement point is located. On another note, through this simple research, the concept of motion in physics can also be demonstrated, showing that objects approaching the earth will have increasing velocities. This study makes a valuable contribution to the development and advancement of education and scientific research.

1.1 Microcontroller

A microcontroller is a microprocessor chip equipped with input/output components and memory, functioning based on programmed instructions. There are many types of microcontrollers available on the market, each with its own advantages and disadvantages. The choice of microcontroller depends on the goals of the system to be built. In this research, an Arduino Nano microcontroller board is used, which employs the AtMega328 chip as the central unit for executing the measurement processes. The pin description for the Arduino Nano is shown in Fig. 1. This research utilizes the Analog Input pins for sensor inputs, defining each sensor in the script as follows:

```
#define sensor1 A0
#define sensor2 A1
#define sensor3 A2
#define sensor4 A3
#define sensor5 A6.
```

This script is written in the program that will be uploaded to the Arduino Nano board via the Arduino IDE. The analog signals from the sensors will be converted into digital signals by the Analog-to-Digital Converter (ADC) present on the microcontroller board.

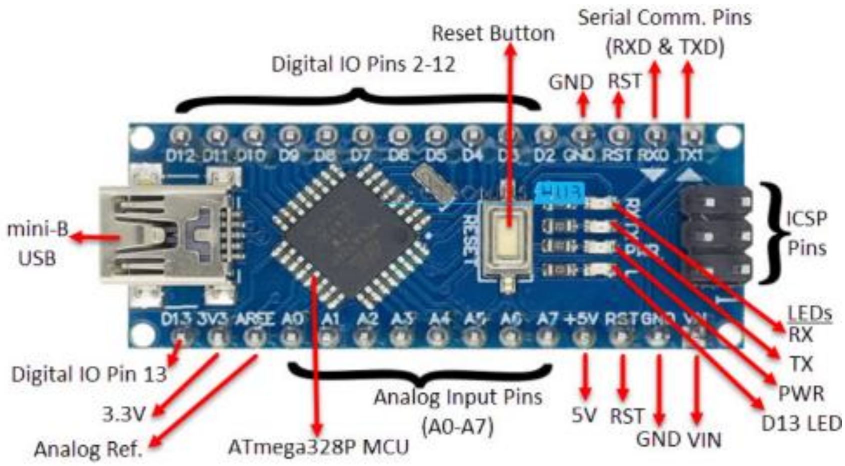

Fig. 1. Arduino Nano board (www.nextpcb.com/blog/arduino-nano-pinout)

1.2 Infrared Sensor

The infrared sensor consists of two main parts: the transmitter and the receiver. The sensor operates based on changes in the receiver's received signal. The transmitter continuously sends signals to the receiver. If an object is located between the transmitter and receiver, the transmitter will send a different response to the receiver. This property is utilized in the system being developed to detect the presence of granular material at a point falling between the transmitter and receiver. To improve measurement accuracy, this research designs a multi-sensor infrared system to detect the presence of falling granular material. The multi-sensor infrared system for the granular flow rate measurement consists of 5 pairs of transmitters and receivers arranged vertically (Fig. 2). This arrangement not only improves measurement accuracy, but it also demonstrates that the concept of free-fall motion can be observed in this system

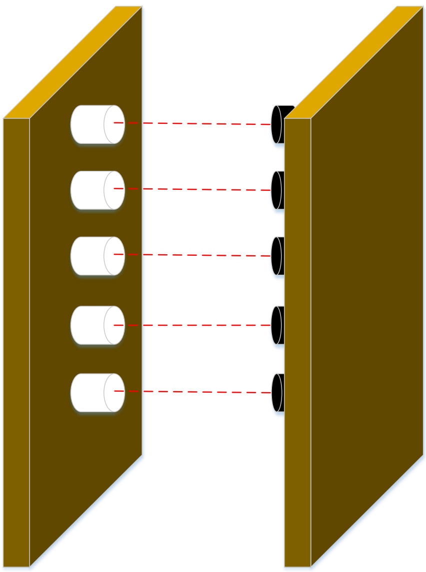

Fig. 2. The multi-sensor arrangement

1.3 Free Fall Objects

Free fall motion is a key topic in the study of kinematics in physics. Numerous studies on this topic have been applied in various fields [25–28]. According to this kinematics material, an object dropped from a certain height will have a changing velocity based on the measurement point. The closer it gets to the earth's surface, the faster the falling object's velocity will increase. The velocity of a free-falling object is only influenced by its height and gravitational force. Fig. 3 depicts a free-falling object's velocity based on its height.

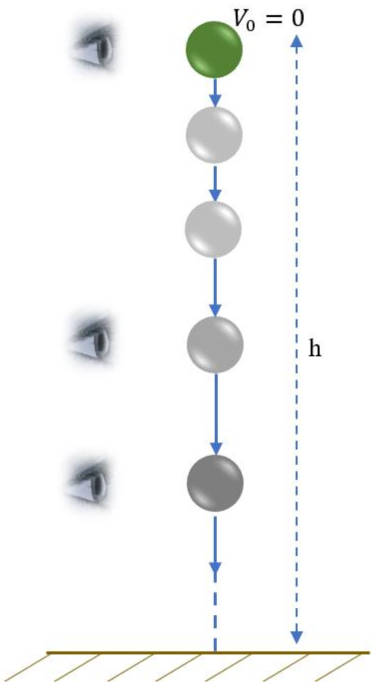

Fig. 3. Free fall object

The velocity based on the distance and time of falling granules measured by sensors will increase according to the distance travelled by the granules, analogous to the equation of free falling objects in basic physics, as in (1-3). h is the height of the falling object, t is time, g is gravity and v_t is the velocity at the measurement point.

$$h = \frac{1}{2} g t^2 \tag{1}$$

$$t = \sqrt{\frac{2h}{g}} \tag{2}$$

$$v_t = g.t = \sqrt{2gh} \tag{3}$$

2. Method

In general, the stages of designing and building the project-based learning system for measuring granular flow rate and testing are outlined in block diagram Fig. 4a. The activities begin with constructing the electronic system consisting of sensors, a microcontroller, and a display. The mechanical part is designed as a medium for positioning the granular material to be tested. Next, we carry out the calibration process of the sensors and proceed to the stage of granular flow rate testing. The flow measurement flowchart conducted by the sensors is shown in Fig. 4b. Calibration is performed simply to determine if the infrared sensors respond to the presence of an object in front of them. During calibration, there are two conditions: when an object is present in front of the sensor, and when no object is present. The output voltage is measured for both conditions. The type of microcontroller used in this research is the Arduino Nano board. Five pairs of infrared sensors are connected to the Analog Input pins of the Arduino Nano board. The pin specifications for the Arduino Nano board can be seen in the previous section.

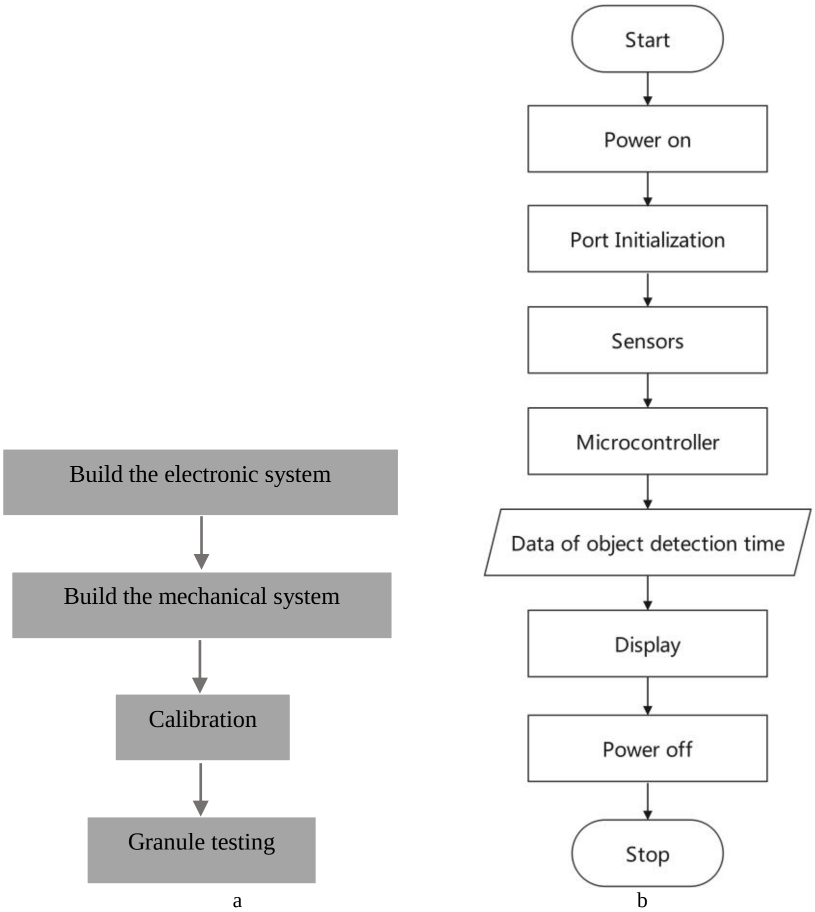

Fig. 4. a. Block diagram of the measurement system. b. Flowchart of script program

2.1. Method of flow rate measurement by sensors

Granular flow rate is measured using five infrared sensors, each consisting of a transmitter and receiver. The sensor will experience a signal change when there is an object between the transmitter and receiver. If the positions of the transmitter and receiver are facing each other, then granules, as the object whose flow rate is to be measured, can obstruct the transmission of infrared light between the transmitter and receiver (Fig. 5). However, granules can also act as infrared (IR) light reflectors from the transmitter to the receiver if the sensor positions are adjacent, as shown in Fig. 6. The receiver in the sensor formation in Fig. 5 will not receive IR light if there are no granules flowing in front of it.

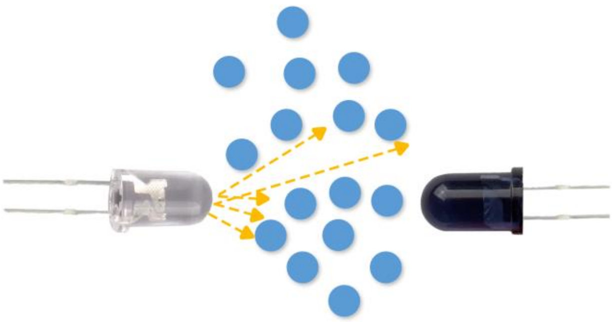

Fig. 5. Principle of granular detection with facing sensor positions

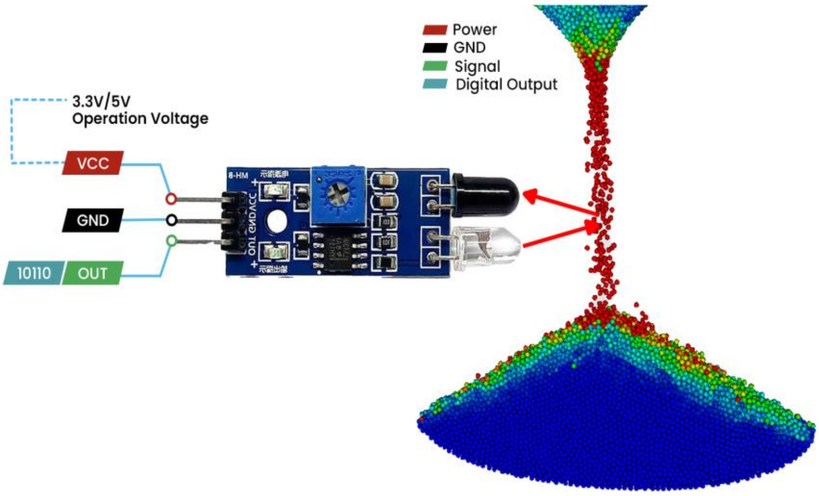

Fig. 6. Principle of granular detection with adjacent sensor positions

The sensor will experience a signal change as soon as granules flow in front of it. For instance, when there are no granules flowing, the sensor sends a 0-volt signal, but when granules are present, the signal changes to 5 volts. The 5-volt voltage will continuously be transmitted until all granules have finished flowing or the granular collection funnel is empty. The duration of the 5-volt signal sent by the sensor represents the flow time required for a certain number of granules. The flow time of granules will be consistently measured by the sensor regardless of its position due to the influence of gravitational force.

2.2. Test Granules

In the granular flow rate measurement stage, several types of granules are used, namely colorstone, citrun, sugar, rice, and basil seeds, each weighing 70 grams (Fig. 7). Granules will be considered of good quality if, when 100 grams of granules are tested, the flow time is not more than 10 seconds. The granules tested in this research are already products of production, so the measured flow time of the100 grams of granules used should not exceed 10 seconds.

Fig. 7. Granules tested in the multi-sensor measurement system

2.3. Mechanical System

The granules are placed in a funnel with a bottom that can be opened/closed automatically. The quantity of granules depends on the volume of the funnel being used The quantity of granules depends on the funnel volume being used. The funnel's vertical position can be adjusted as needed and stabilized using static poles and clamps.

2.4. Electronic System

The microcontroller, sensor, LCD/display, and several other components are essential parts of the electronic system for measuring granular flow rate. The microcontroller used is from Arduino, which will process all the data/signals sent from the sensor and then display them on the LCD and Arduino's serial monitoring on the computer. The sensor will send real-time digital data to the microcontroller, allowing for the measurement of the flow time of a certain amount of granules as they pass through the sensor. Once both the mechanical and electronic parts are properly functioning, the two parts will be integrated into a unified flow rate measurement system.

The system integration begins with connecting the mechanical part's granular funnel cover to the servo motor arm. According to the measurement start command, the servo will move to open and close the granular funnel cover. Next, the five pairs of sensors are positioned or arranged vertically directly beneath the funnel, where the granular flow occurs.

2.5. Testing

Each type of granule will be tested repeatedly (5 times) to determine its flow time. The granular flow time is obtained using simple statistics, specifically by averaging the flow time for each repetition and each sensor. When the on button or electronic part is activated, the bottom cover of the granular funnel will open, and the granules will flow in front of the multi-sensor. Measurement data from the sensors will be displayed on the Arduino's serial monitor on the laptop. The data includes the measurement time down to milliseconds, as well as the on/off signal indicating the presence or absence of granules. After all the granules have flowed from the funnel, deactivate the on button to finish measuring. The obtained flow times will then be further analyzed to determine the granular flow rate, usually expressed in grams per second.

3. Result and Discussion

Result

3.1. The granular flow rate measurement system

Fig. 8 shows the granular flow rate measurement system with multiple sensors. This system uses a 30 x 25 cm base stand with a 45 cm pole height. The granular collection funnel has dimensions with a top diameter of 7.5 cm, a bottom diameter of 1.4 cm, and a height of 7.5 cm. The funnel holder is designed to be non-permanent, allowing the granules to be flexibly dropped from various heights corresponding to their position on the pole.

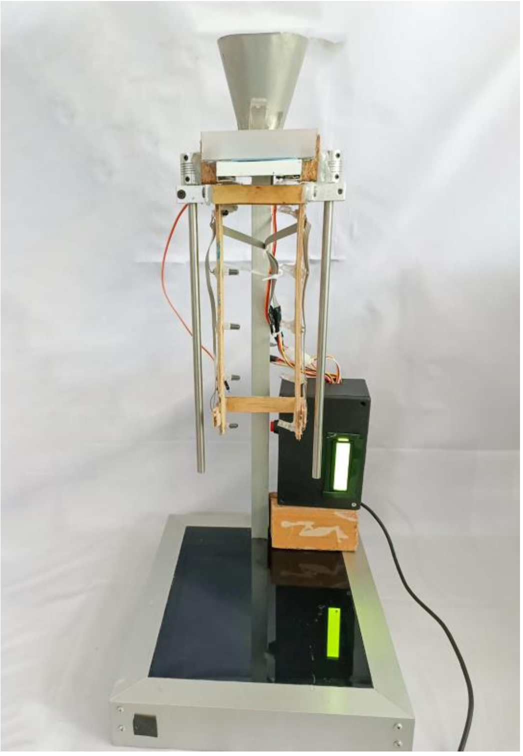

Fig. 8. Multi-sensor granular flow rate measurement system

The electronic components of the granular flow rate measurement system are placed separately next to the funnel. When measuring the granular flow rate, the bottom cover of the funnel is opened by pressing the open button on the electronic box, allowing the granules to fall between a pair of transmitter and receiver sensors that detect the presence of objects in front of them. The opening and closing of the funnel are controlled by a servo motor. When the button is turned on, the servo will retract the funnel cover to open it, conversely, when the button is turned off, the servo will return the funnel cover to its original position (closed). The position of the servo motor can be seen in Fig. 9.

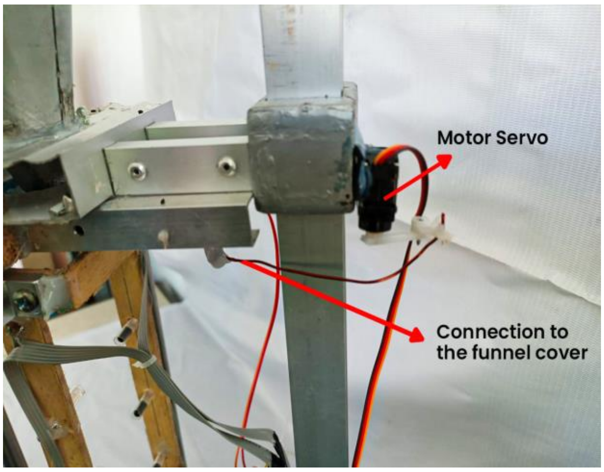

Fig. 9. A servo motor for opening and closing the funnel cover

When an object (granule) is in front of the sensor, the indicator light on the electronic box will illuminate (Fig. 10). The indicator light's duration indicates how long it takes for the granule to flow. The sensor will send a high signal to the microcontroller via serial communication, and this signal will be transmitted to a personal computer (PC) connected to the Arduino's serial monitoring. When all the granules have finished falling or there are no more flowing in front of the sensor, a low signal will appear on the serial monitor. The duration of the high and low signals will be displayed on the serial monitoring on the PC. The measured granular flow time from the system, along with the known mass of the tested granules, will then be used to calculate the flow rate, expressed in grams per second.

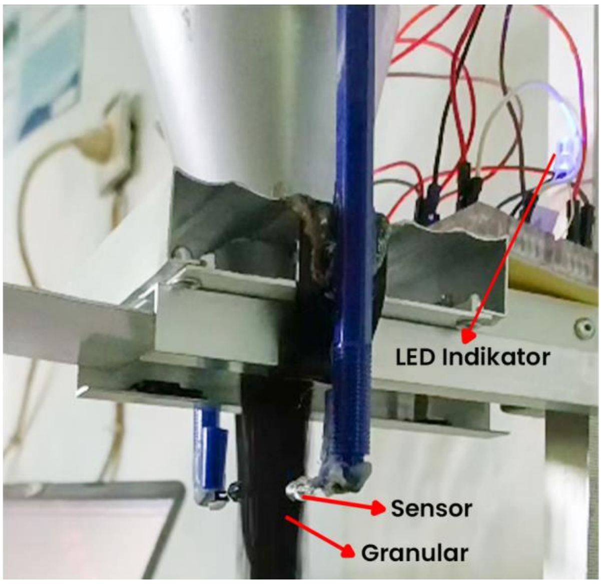

Fig. 10. Indicator lights on the measurement system

The multi-sensor granular flow rate measurement system employs five pairs of infrared sensors positioned beneath the funnel's surface at incremental distances. The top sensor (sensor 5) is located 5 cm below the surface of the funnel, the next sensor (sensor 4) is positioned 10 cm from the bottom surface of the funnel, and so on until the last sensor (sensor 1) is 25 cm away from the bottom surface of the funnel. Fig. 11 shows a detailed diagram of the multi-sensor installation.

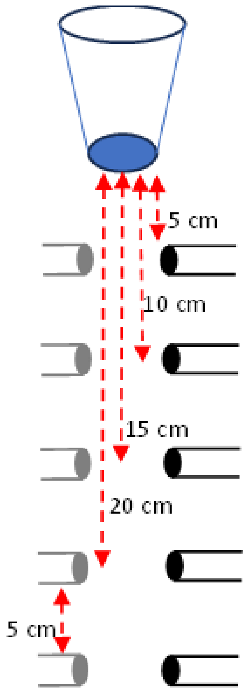

Fig. 11. Diagram of multi-sensor installation

When the granules are in front of the multi-sensor or falling from the funnel, the sensor will send a high signal to the microcontroller via serial communication. This signal will then be transmitted to a personal computer (PC) connected to the Arduino's serial monitoring and displayed on the LCD. When all the granules have finished falling or there are no more flowing in front of the sensor, a low signal will appear on the serial monitoring. The duration of the high and low signals will be displayed on the serial monitoring on the PC and the LCD (Fig. 12).

Sensor 5 is the sensor that will respond first when the granules are dropped from the funnel because sensor 5 is the closest (5 cm) to the base of the funnel. On the other hand, sensor 1 is the farthest from the base of the funnel, so the object in front of it has the last detection time.

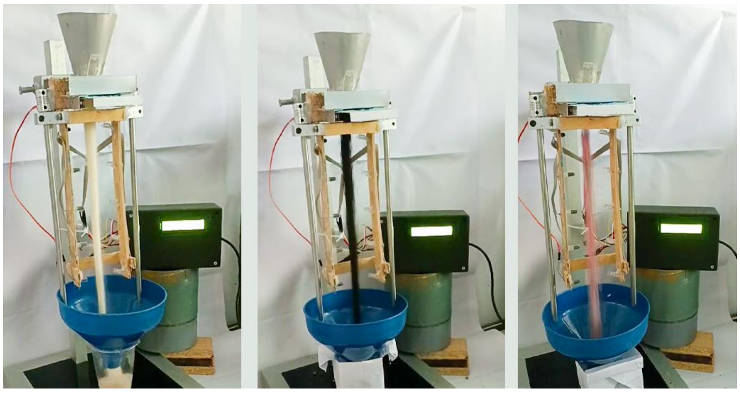

Fig. 12. Granular testing

The infrared sensor detects the presence of objects in front of it as quickly as every 0.001 second. During flow rate measurements, the sensor detection speed is adjusted using a script uploaded to the microcontroller in a delay format. The primary data obtained from reading/measuring multiple sensors is the flow time data (the time taken granularly with a certain mass to fall from a certain height). Fig. 13 shows that with the same mass, colorstone granules take less time to flow from the funnel and be measured in front of the multi-sensor compared to basil seeds and other granules.

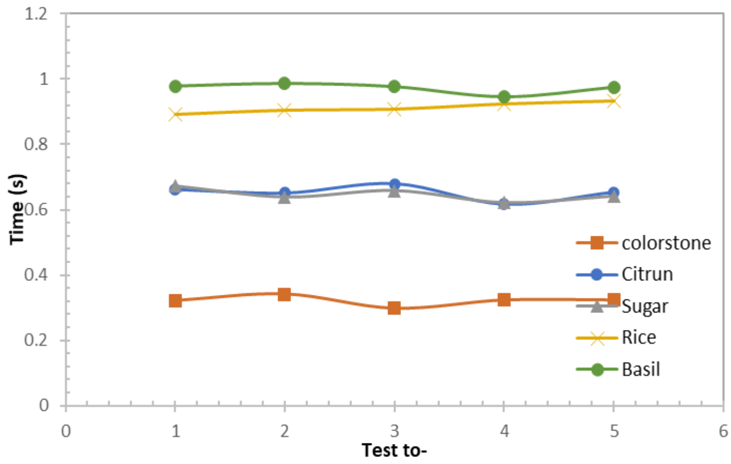

Fig. 13. Granular flow time across multiple sensors

3.2 Granular Flow Rate

The flow rate can be determined by calculating the flow time and mass of each tested granular material. Using simple descriptive statistics, the granular flow time is obtained from the mean value of each type of granular material across repetitions. Each material has a consistent tested mass of 70 grams. Therefore, the flow rate of each granular material can be expressed in grams per second (g/s), as shown in Table 1.

Table 1. Granular Flow Rates with Multi-Sensor System

No	Granule	Mass (gram)	Flow rate (gram/s)					
			S 1	S 2	S 3	S 4	S 5	Average
1	Colorstone	70	217,1	205,0	233,4	216,1	216,1	217.54
2	Sugar	70	104,5	109,4	107,7	112,9	109,4	108.78
3	Citrun	70	105,8	107,5	103,1	113,2	107,0	107.3
4	Rice	70	78,4	77,3	77,3	75,7	74,5	76.64
5	Basil	70	71,5	70,9	71,7	74,1	71,8	72

Furthermore, employing the concept of free fall motion in physics, it can be observed that the velocity of falling granules increases as they approach the ground surface. The velocity of falling granules is calculated using equations (1-3) at each sensor. Objects in free fall are assumed to be solely influenced by gravitational force. In this multi-sensor system, the sensors are arranged vertically to measure the velocity of granules moving in front of them. Sensor 1 is the closest to the ground surface, and theoretically, in free fall motion, the velocity of granules measured by this sensor is expected to be the highest compared to other sensors in the system. The granular velocity readings from the multi-sensor system are shown in Fig. 14.

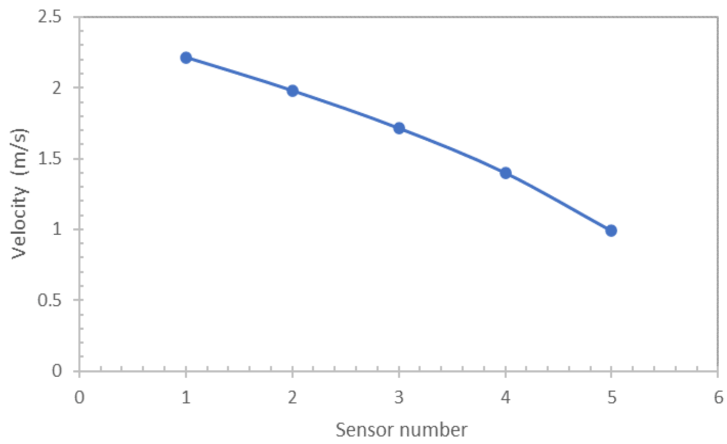

Fig. 14. Falling velocity of colorstone granules in the multi-sensor system based on measurement points

Discussion

In general, project-based learning emphasizes the integration of knowledge [4], as demonstrated in this research. The final product of the project-based learning system for granular flow rate measurement, based on a microcontroller and multi-sensors, is a device that can validate the synchronization of theoretical knowledge with its application.

In the process of granules falling from the funnel, the concept of free fall motion in physics applies, where the closer the object is to the center of the earth, the faster the falling object with an initial velocity of zero will increase, neglecting air resistance. According to this concept, the first sensor, which is closest to the ground, will detect the granular material's highest falling velocity. This theoretical concept has also been validated in other project-based learning activities that study gravitational values through laboratory-scale free-fall tests [29].

Next, we explore how the mass of a material can affect the flow rate of the object. This is illustrated in Fig. 13. Seventy grams of basil seeds take more than 0.9 seconds to flow completely from the funnel. In contrast, 70 grams of colorstone only take about 0.3 seconds to flow completely from the funnel. This can be attributed to the significantly different densities of the two granular materials, with basil seeds having a higher density compared to colorstone granules. Visibly, 70 grams of basil seeds would occupy a larger space/volume compared to 70 grams of colorstone. These results align with the research conducted by Jack Tian and Clifford Whitfield, which states that the flow of an object is influenced by its mass. In this study, the object's mass was varied, and the object's flow was observed. The findings indicated that, upon release, objects with greater mass exhibited higher flows compared to those with less mass [30].

The flow time of a granular material measured by five sensors is nearly identical (Fig. 13). For example, for citrun granules, the flow time measured by sensors 1 through 5 is approximately 0.6 seconds. This indicates that the flow time of the granular material is measured, whether it is close to the funnel base or further away from the funnel, the flow time of the granular material remains the same.

Based on Table 1, it is evident that generally, all tested granular materials have met the minimum standard for the requirement of a suitable granular material for production, which is > 10 grams/s. Colorstone granules have the highest flow rate. The measured flow rates at all sensors are nearly identical, with a maximum error of 7.1% for colorstone granules.

In Fig. 14, it's evident that the highest falling velocity occurs with colorstone granules, as shown at measurement point sensor 1, which is 2.2 m/s. This is because sensor 1 is positioned closest to the ground surface, resulting in the highest falling distance. Meanwhile, the lowest falling velocity is measured by sensor 5, which is 0.98 m/s, with the smallest falling distance and positioned furthest from the ground surface. This has demonstrated that free-falling objects will have an increasing velocity as they approach the earth's center.

4. Conclusion

A multi-sensor-based granular flow rate measuring system has been constructed using Arduino Nano microcontrollers. For flow rate measurements, the multi-sensors are arranged vertically. The mechanical part for collecting granules is controlled by a servo motor to initiate the dropping of test granules. The multi-sensor concept used for granular flow rate measurement can validate classroom learning concepts and demonstrate the flow rate of materials required for large-scale granular production in the future. When testing the properties of granular flow rate, it was discovered that colorstone granules have the highest flow rate compared to other test materials. The concept of free fall motion aligns with the test results obtained, indicating that objects in free fall will have different falling velocities depending on the falling distance. This project can be further developed to meet the needs of project-based learning and research, with more visualization in the form of graphics and other educational fields. This development will have implications for the integration of project-based learning (PBL) with empirical research to address societal and industrial needs, as well as advancements in mechanics analysis, particularly in the topic of free fall.

Acknowledgment

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