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Mechanical Energy Conservation Investigation Using Photodiode Sensor Based on Arduino Uno

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Abstract. Mechanical energy (*ME*) is the sum of potential energy (*U*) and kinetic energy (*K*) and associated with the motion and position of an object. The values of *ME* will always perpetually if the force is constant, while the value of *K* and *U* depend on the object position. This study aims to design an apparatus for investigation of the mechanical energy conservation experiment through free fall events using three point photodiode-sensor measurements based on Arduino Uno platform. A prototype is made from PVC cylinder of 100 mm diameter and a height of 100 cm, holed with a height of 100 cm, holed with surface pattern to minimize air friction inside the tube and the acceleration of falling objects is equivalent to the acceleration of the earth's gravity, which is 9.8067 ms^{-2}. Three photodiode sensors are installed straight on the prototype belt to enable the receiver collects light directly from the transmitter while the second sensor is movable up and down to latch the ball travel time, time between interrupts is then measured as well as *U* and *K* on an interface. The experiment shows that the decrease in *U* is proportional to the increase in *ME*, where the *U* of objects decreases by 0.0099 Joule every 100 mm distance while *K* of objects increases by 0.0098 Joule. In the middle of the cylinder with the height of falling objects is 50 cm, then $U = K$, so the *ME* value has remained constant.

INTRODUCTION

Mechanical energy is the result of the sum of kinetic energy with potential energy which is influenced by the height of objects [1]. Mechanical energy will be constant if there is no force acting on objects other than gravity. Gravitational is one of the conservative forces since the effort made on objects depends only on the final position and the beginning of the object [2]. The concept of mechanical energy is very challenging to understand by students in secondary schools, where [3] states that 72% of students in grade 10 have difficulty understanding the material about mechanical energy.

Mechanical energy can be observed in the event of free fall that occurs in a very short time, so it requires a tool with high accuracy to record the travel time of objects when moving freely. The accuracy of recording travel time is very important in this tool, because the acceleration of an object must be equivalent to the acceleration of the Earth's gravity, in order to obtain the right mechanical energy conservation value.

Bunker [4] has developed an experimental tool for free fall motion using magnetic sensors made from 25 mm brass ball in diameter. This tool the acceleration of falling objects is equivalent to the acceleration of gravity, but does not explain the conservation of mechanical energy in that event, and the accuracy of this object is quite low, with an error: 1.87%. An experimental tool for free fall motion has been developed using photodiode sensors [5]. This study aims to investigate the coefficient of restitution from collisions in the event of free fall motion, with a value of $0 < e < 1$. The experimental tool enables to demonstrate that the acceleration of falling objects during free fall is equivalent to the acceleration of Earth's gravity, with an error of 0.34%, but this tool does not investigate mechanical energy conservation and how the tendency of *K* and *U* when the free fall occurs.

The research on the mechanical energy conservation investigation tool has been done by [5] by designing an experimental apparatus in the form of spider wheel, which can show the effect of rotational and translational velocity changes due to linear and rotational kinetic energy. However, this tool cannot show changes in kinetic and potential energy at any altitude. Theodoros and Hariton have also developed an experimental apparatus to study the conservation

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of mechanical energy using the integrated acceleration sensor on the smartphone as a pendulum mass and accelerometer [6]. The result agreed with the theory, which has a correlation coefficient (r^2) of 0.9957, despite kinetic and potential energy as the main parameter of mechanical energy cannot be directly determined. Development of mechanical energy experimental apparatus was also carried out using infrared sensors to detect the speed of moving objects [7]. The study demonstrated the conservation of mechanical energy as the object moving freely with an error of 1%, however *U* and *K* and the influence of both energies against *ME* values cannot be determined at a certain distance.

In this work, a tool was developed to investigate the mechanical energy of objects based on free fall motion using three pairs of CQY99 LEDs sensors and an SF2020FA photodiode sensor mounted on a PVC tube with a length of 120 cm, an outer diameter of 11 cm and an inner diameter of 10 cm. The three pairs of sensors will be installed at three different measurement points, where sensor 2 is moveable, so that it can detect EM objects when they have traveled at a certain distance. The position of sensor 2 is enabled to investigate the law of mechanical energy conservation using trace time of objects when traveling a certain distance after falling event. The travel time data is used to determine changes in kinetic energy and mechanical energy of objects. The measurement results are then displayed on the interface in the form of data and graphics.

METHOD

Mechanical energy in free fall events involves many physical quantities that affect its value, as shown in Fig. 1 below.

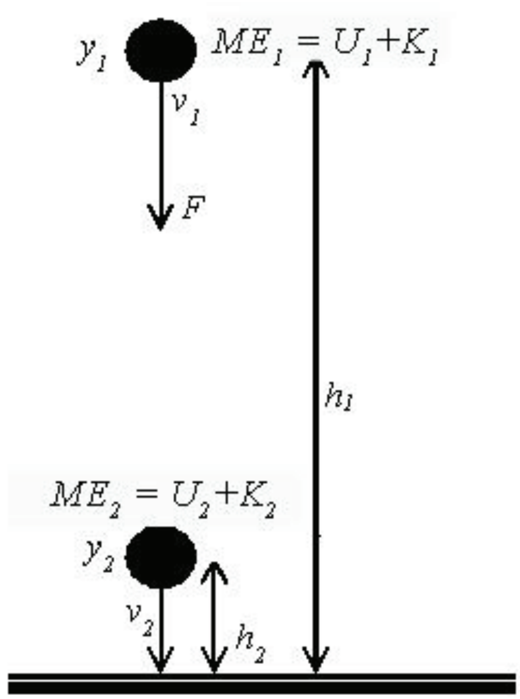

FIGURE 1. Mechanical energy in the event of free fall

Figure 1 describes that when a moving object falls freely, a constant force *F* makes an effort so that objects with mass *m* move as far as *y*, then the effort carried out by that force can be written as:

$$W = \int_{y_2}^{y1} F \cdot \partial y \tag{1}$$

Based on Newton's law $F = ma = mdv/dt$, the work can be defined:

$$W = \frac{1}{2} m v_2^{\,2} - \frac{1}{2} m v_1^{\,2} \tag{2}$$

Magnitude of 1/2 mv^2 is the kinetic energy of an object, which is the energy, possessed by an object with mass m because of its motion (v), then:

$$K = \frac{1}{2} m v^2 \tag{3}$$

Figure 1 depicts the objects with mass m moving along the vertical axis y while the force acting on objects is gravity $w = mg$. The object falls down in the direction of gravity, so the effort made by gravity to drop the ball from position y_1 to y_2 is:

$$W = Fs = mgh_1 - mgh_2 \tag{4}$$

Product of gravity with height is called the potential energy,

$$U = mgh \tag{5}$$

The potential energy objects at positions y_1 and y_2 are expressed as U_1 and U_2 respectively, whereas K objects are conveyed as K_1 and K_2, so the conservation of mechanical energy (*ME*) of objects can be expressed as [8]:

$$U_1 + K_1 = U_2 + K_2 \tag{6}$$

Free fall events occur in a very short time, so it takes a tool with high accuracy to record the travel time of objects when moving freely. The accuracy of recording travel time is very important in this tool, because the acceleration of an object must be equivalent to the acceleration of the Earth's gravity, in order to obtain the right mechanical energy conservation value.

In this work, LED sensors of CQY99 and the photodiode sensor of SF203 FA with emitted light waves at a wavelength of 950 nm are used for experimentation tools. The sensor resistance will change when exposed to light sent by the LED [9]. As the light intensity reaches the sensor, the electric current will flow as a linear function of light intensity [10]. The working principle of the photodiode sensor is shown in Fig. 2.

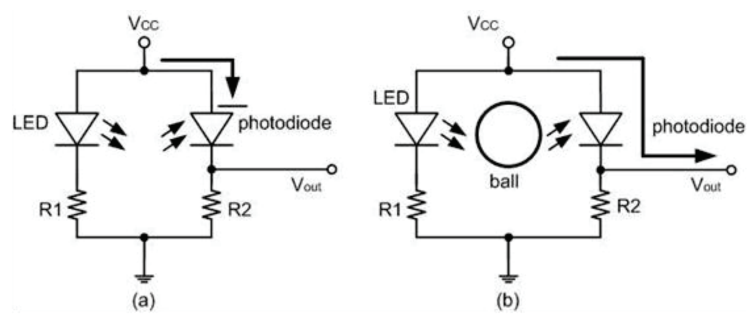

FIGURE 2. The working principles of photodiode sensors to detect free motion object on its light path

Figure 2 (a) is the initial condition of the LED as the light transmitted by the LED is received directly by the photodiode, so the V_{out} value is close to zero logic (low), while in figure (b) the LED light is blocked by objects, so the V_{out} value approaches the V_{cc} value of logic 1 (high) [11].

The sensor work system settings use the Atmega328-based microcontroller on the Arduino Uno board which is activated via a USB connection or an external power source from an AC-DC adapter or battery. This board can operate using external inputs from 6 - 20 Volts [12]. This board has also 14 digital pins that can be used as input and output with R_{int} from 20 to 50 kΩ, while the software allows simple textual data communicate with the Arduino board [13]. Instrumentation system configuration of the circuit for measuring the time difference of the falling objects using three sensors is illustrated in Fig. 3.

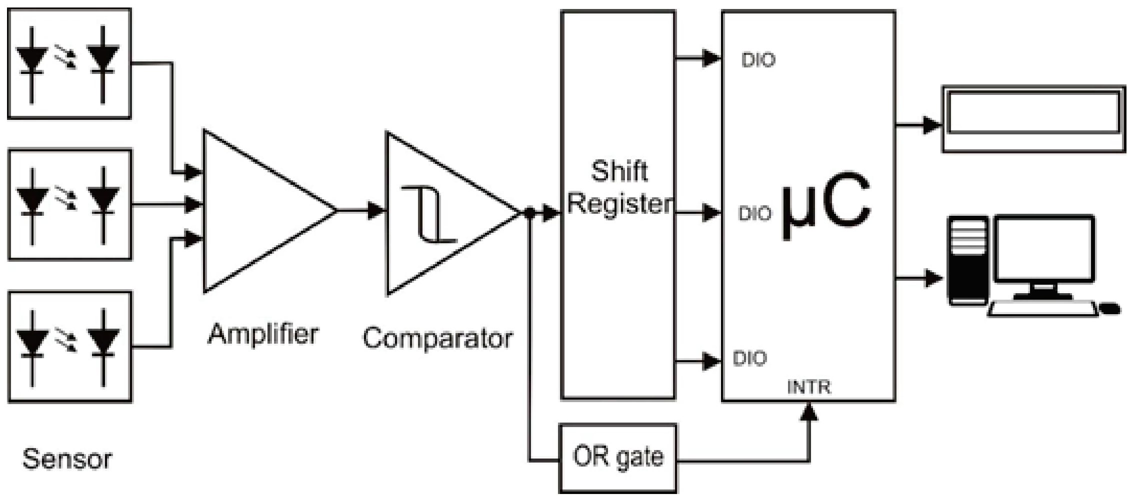

FIGURE 3. Instrumentation system for mechanical energy investigation tools

In Fig. 3, three photodiode sensors are installed using the straight line principle, where the receiver directly acquires light from the LED on its path. The sensor output is an analog voltage which depends on the intensity of light received from the LED. Furthermore, the signal is amplified and converted to digital by the comparator using the Schmitt trigger principle so that small fluctuations or noise in the analog input signal does not change the comparator output quickly. The output of the comparator will be regulated by the shift register, so that when the circuit is reset, all outputs will be zero logic.

Data is entered in parallel on the input shift, consequently the data register will be issued in parallel while the flip-flop gets a signal from logic 0 to logic 1. The output of the shift register is connected to the DIO microcontroller digital input and the "OR" logic gate. The logic gate "OR" is needed to trigger the interrupt (INTR) which functions to notify the circuits that a condition has changed from the sensor. This indicates that the object passes through one of the sensors, so the microcontroller can check the active sensor via DIO input. The time between INTR is calculated by checking the corresponding sensor. The time value of the calculation result is displayed through a display and the *ME* values, *U*, and *K* are displayed in the interface. The *ME*, *U* and *K* calculation systems from system measurement data are processed using Visual Studio 2010, based on C# language. The microcontroller and Visual Studio work logic system in this tool can be seen in Fig. 4.

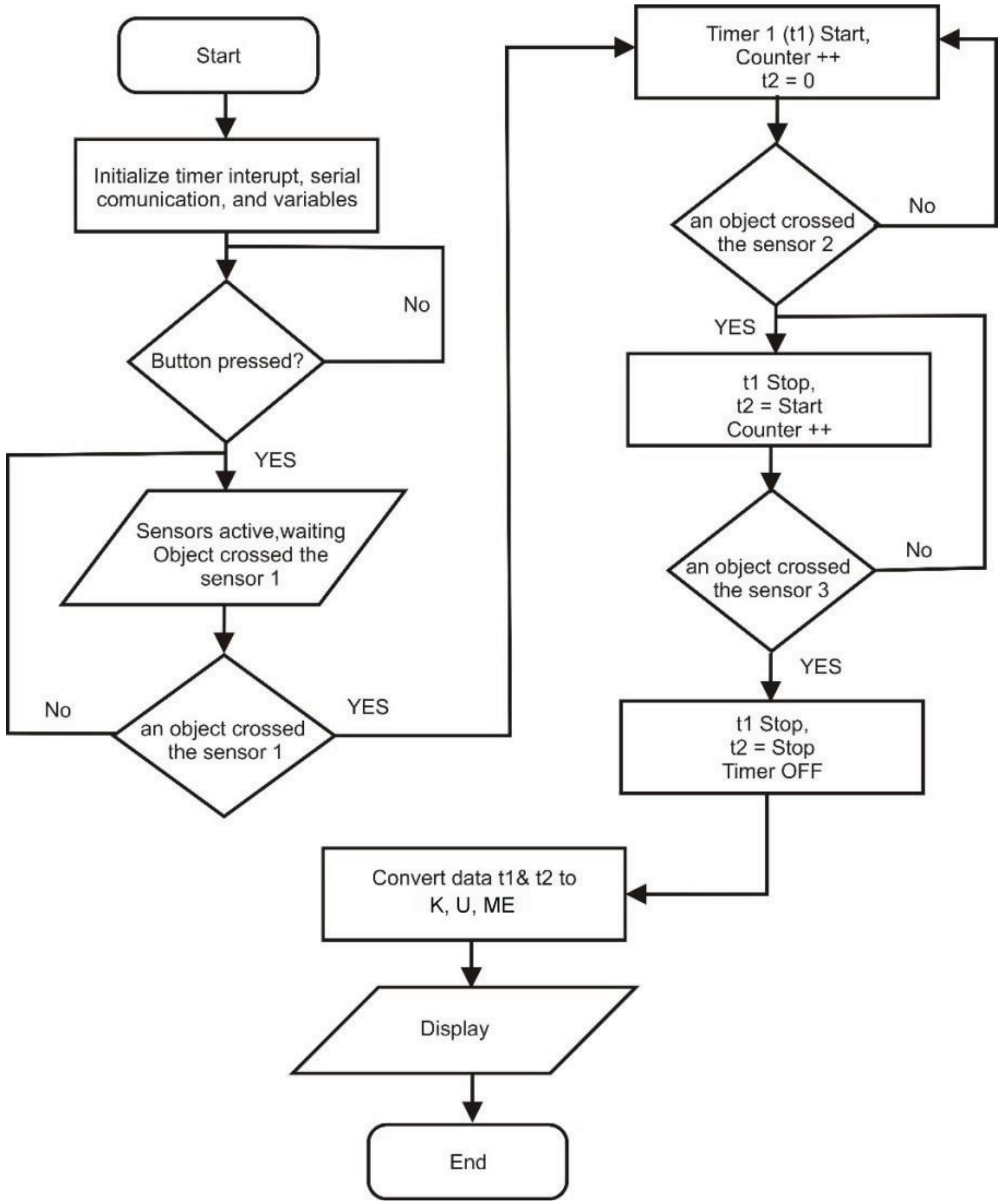

FIGURE 4. Flowchart system logic tool

The instrumentation system is installed in a prototype made of PVC pipe with a diameter of 110 cm and a thickness of 5 cm with a height of 120 cm. The prototype consists of separate parts, but it is easy to assemble and disassembled when it is used and stored and also very easy to carry and move.

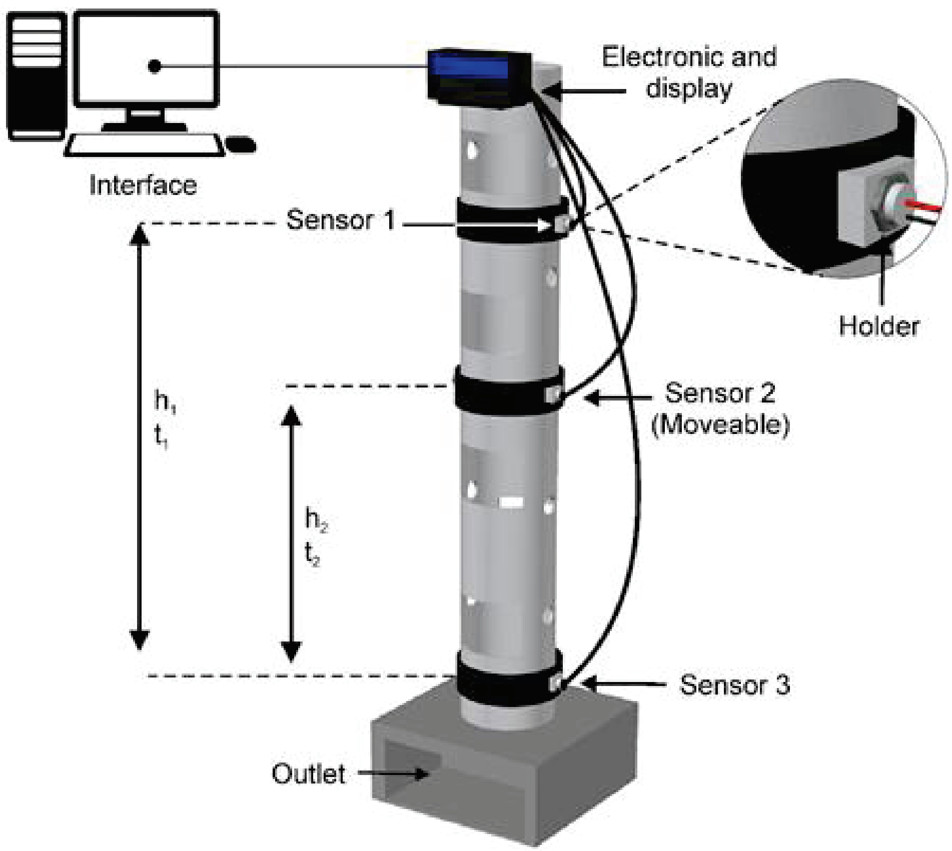

FIGURE 5. Prototype of a mechanical energy investigation tool

The surface of the PVC tube is perforated by an alternating pattern with a size of 80 x 80 cm to reduce air friction in the tube so that the acceleration of measuring balls is equivalent to the acceleration of gravity 9.8 ms^{-2}. A plastic ball with a diameter of 60 cm and a mass (*m*) of 10 grams is used as a free fall object and at the bottom of the prototype tube, a base made from wood is installed as bouncing surface with ball outlet so that the prototype does not easily collapse. The measuring ball drops through the door at the top of the tube which will detach itself when the piston on the tube door is pulled. The working system of tools for mechanical energy investigations, *U* and *K* is as follows:

- Sensors 1 and 3 are ON, with sensor position 1 at a point 100 cm (h_1) and sensor 3 at zero point.
- Data obtained from measurement results is the time of dropping objects from sensor 1 to sensors 3 (t_1), h_1 and m.
- The next measurement of all sensors is activated, and the position of sensor 2 is varied at the point of 90 cm, 80 cm, 70 cm, 60 cm and 50 cm.
- Data obtained from measurement results are distanced from sensor 1 to sensor 2 (s), distance from sensor 2 to sensor 3 (h_2), and trajectory time of objects from sensor 2 to sensor 3 (t_2).
- Potential energy values obtained from calculations using equation (5), *K* values with equation (6) and *ME* values with equation (6). The values of *U*, *K* and *ME* are displayed on the interface in the form of tables and graphs.

RESULT AND DISCUSSION

The prototype of this experiment is equipped with a movable sensor, so that this tool can be used to investigate the tendency of *U* and *K* when moving freely and to observe the relationship between these two values towards mechanical energy values. The results of the mechanical energy investigation experiment are shown in Fig. 6.

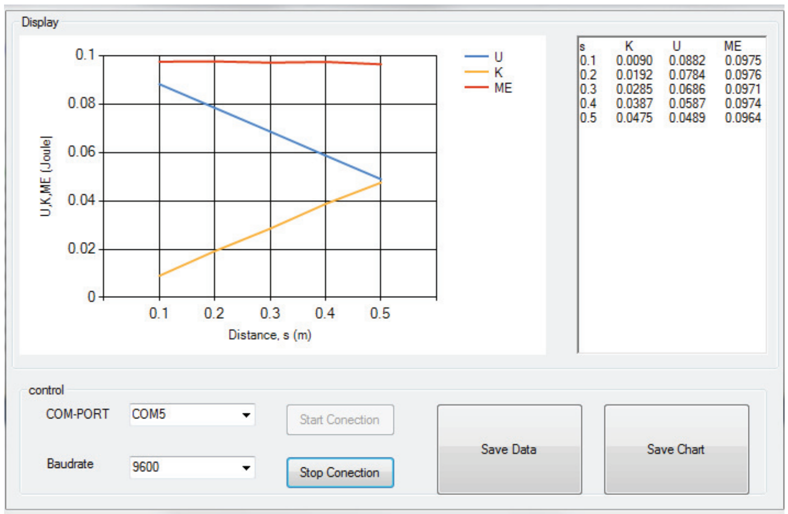

FIGURE 6. The display shows the mechanical energy experiment

Figure 6 shows the sensitivity of the sensor to the objects denoted by baudrate, which represents the speed of data retrieval of 9,600 kbps. Since a byte of data requires data transfer as much as 8 bits per second, then this tool transfers data has 76,800,000 bits of data per second. As the ball falls down, the data immediately appear on the interface in the form of data tables and graphics that allow the students to understand the concept of energy conservation material for any heights. In the menu interface, there is also a menu of saving data and a save chart so that the measurement can be saved and enabled to make new reductions without deleting the previous data.

The mechanical energy value of a moving freely falls ball tends also to be constant with a mean of 0.0972 Joule and an error of 0.033%. In Fig. 6, as the moving ball falls freely, then *U* of the ball gets smaller since the ball gets closer to the earth, while the *K* gets larger and vice versa. This result agrees with the theory stated *U* linear with respect to altitude, whereas *K* is linear to the speed and the ball will move faster when moving closer to the earth. As the ball reaches a distance of 0.1 m, *U* was 0.0882 Joule and after traveling a distance of 0.2 m, the *U* was reduced to 0.0784 Joule. However, *K* ball increases from 0.009 Joule to 0.0192 Joule for traveling the same distance. The decrease in *U* and increase in *K* at these two points has the same results of 0.0095 Joule for both. So this agrees with the theory of energy conservation where energy is eternal. At a half distance by measuring tube and $h_1 = h_2 =$ 50cm, $U = K$, so that the sum of the values of *U* and *K* for any measuring height has a relatively constant mechanical energy value. At the highest position, the mechanical energy is dominated by the ball potential energy and when the ball has fallen the mechanical energy begins to change into kinetic energy and closer to the earth the kinetic energy gets higher than potential energy. Based on this experiment, it can be explained to students about the conservation of energy law and the tendency of *U* and *K* as a function of the height of the free fall ball.

CONCLUSION

A tool for determining mechanical energy based on the principle of a free fall ball that has been successfully made based on three-sensor configuration. Sensor 2 is moving at the sensor configuration and is enabled to investigate the changing of *U* and *K* of the measuring ball that moves freely. Changes in *U* and *K* obtained in accordance with the theory, where the *U* value decreases with increasing value of *K*, but the change in the second value of energy is relatively the same so that the value of mechanical energy measuring balls is relatively constant with 0.092 Joule and small error of 0.033%.

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