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A simple distance measurement instrument based on the law of light reflection

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Abstract
Measurement instruments of physics, especially those dedicated as teaching aids in physics classroom are improving. These measuring instruments are not only used for measurement purposes, but also to apply theoretical concept into the real world, thus making it easier for students to comprehend. Therefore, this study aims to design, construct, and test a distance-measuring instrument based on the law of light reflection, especially for teaching physics. The method used in this study is quantitative-descriptive method, with the stages of designing, constructing, developing, and testing the distance-measuring instrument. The measuring instrument is constructed from simple, inexpensive, and easily obtained tools and materials, and it is an improvement version of a similar instrument previously developed. The testing stage of this instrument shows that the distance measurement results using the instrument is in good agreement with the results using a ruler depending upon the fixed flat mirror angle of the instrument.

1. Introduction

One important activities in physics and physics learning is taking measurements. By conducting measurements students may understand the physical properties of the system under consideration or prove the validity of a physical theory. In the aforementioned activity, the measuring instruments used are the results of innovations or new discoveries that should be inexpensive, simple, and easy to use [1]. An innovative measuring instrument should produce the best level of accuracy and precision [2]. In addition, innovative measuring instruments provides choices for physicists conducting the measurements in accordance with their goals. Hence, innovative measuring instruments are a vital component in measurement activities, especially in physics and physics learning.

The existence of measuring instruments makes physicists able to conduct investigations into natural phenomena that occur in everyday life [3]. In addition, innovative measuring instruments developed by physicists can also be used for educational activities. Innovations in measuring instruments in education should also be done for physics teaching aids [4]. The teaching aids used by physics teachers are in the form of physical demonstration aids or modifications to measuring instruments [5]. The existence of teaching aids in physics learning activities not only aims to facilitate students in learning the material presented, but also to increase students' interest, creativity, and problem solving abilities [6]. Schools have provided various physics teaching aids so that teachers and students can directly use them. However, these physics aids are limited in number, especially in developing countries. Therefore, to overcome this limitation, innovations are needed to develop simple, inexpensive, and easy to operate measuring instruments. Hence, good physics aids are those that are inexpensive, easy to make (from simple materials), and easy to operate [7, 8].

One of the most widely used instruments in physics and physics learning is a ruler to measure the length of objects or the distance between objects [1]. Distance measurement between objects can also be done using an ultrasonic sensor in a microcontroller, but this requires complex electrical circuits [9]. In this study, a simple innovation of distance measuring instrument is put forward especially for physics learning purposes based on a physics subject, i.e.: optics.

Developing a distance measuring instruments for physics learning in a classroom that apply optics is rarely done [10], although the concept of optics itself has been used in surveying [11] and astronomy [12]. A distance measuring instruments has been developed using optics concept with accuracy and precision of 97.61% and 97.63%, respectively. However, the developed instrument has only one independent variable and are not efficient in terms of its use [13]. Meanwhile, the concept of measuring instrument that is based on optics is still considered to be difficult by students [14, 15].

A physics law that exists in the concept of optics is the law of light reflection. It states that (i) incident ray, reflected ray, and the normal to the surface of a flat mirror lie in the same plane, and (ii) the angle incident, i, is equal to the angle of reflection, r or $r = i$. This may be observed in figure 1. For educational purposes, the law of light

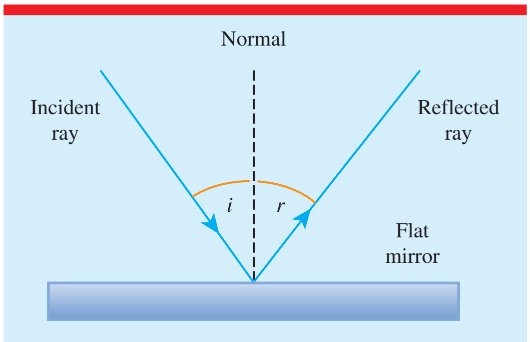

Figure 1. A schematic illustration of the law of light reflection.

reflection has been applied, e.g. to study conics geometry [16]. In this study a distance measuring instrument is developed and tested by applying the law of light reflection. This is done by perfecting the deficiencies that exist in the instrument developed by previous researchers in [13]. One of the main intention in this study is to give students experience in applying the light reflection law in a form of a measuring instrument as a follow up to its theoretical concept. Hence, the main point of this study is to produce a simple, inexpensive, and easy to use distance measuring instrument that can be performed and demonstrated as a physics teaching aid in a classroom. Furthermore, we compare the distance of objects resulted from the instrument and a ruler to validate our results.

2. Research method

The purpose of this study is to design, construct, and test the distance-measuring instrument, which is based on the law of light reflection. Furthermore, we also discuss the applicability of the measuring instruement as a physics teaching aid. This study is a descriptive-quantitative research with stages consisting of (i) designing, (ii) constructing, (iii) developing, and (iv) testing the distance-measuring instrument.

The first stage is to design a distance-measuring instrument by applying the law of light reflection. This stage consists of (i) choosing a topic of a physical measuring instrument, which in this case is a distance-measuring instrument, (ii) studying the limitations in the distance-measuring instrument that has been developed previously, and finally (iii) modifying the distance-measuring

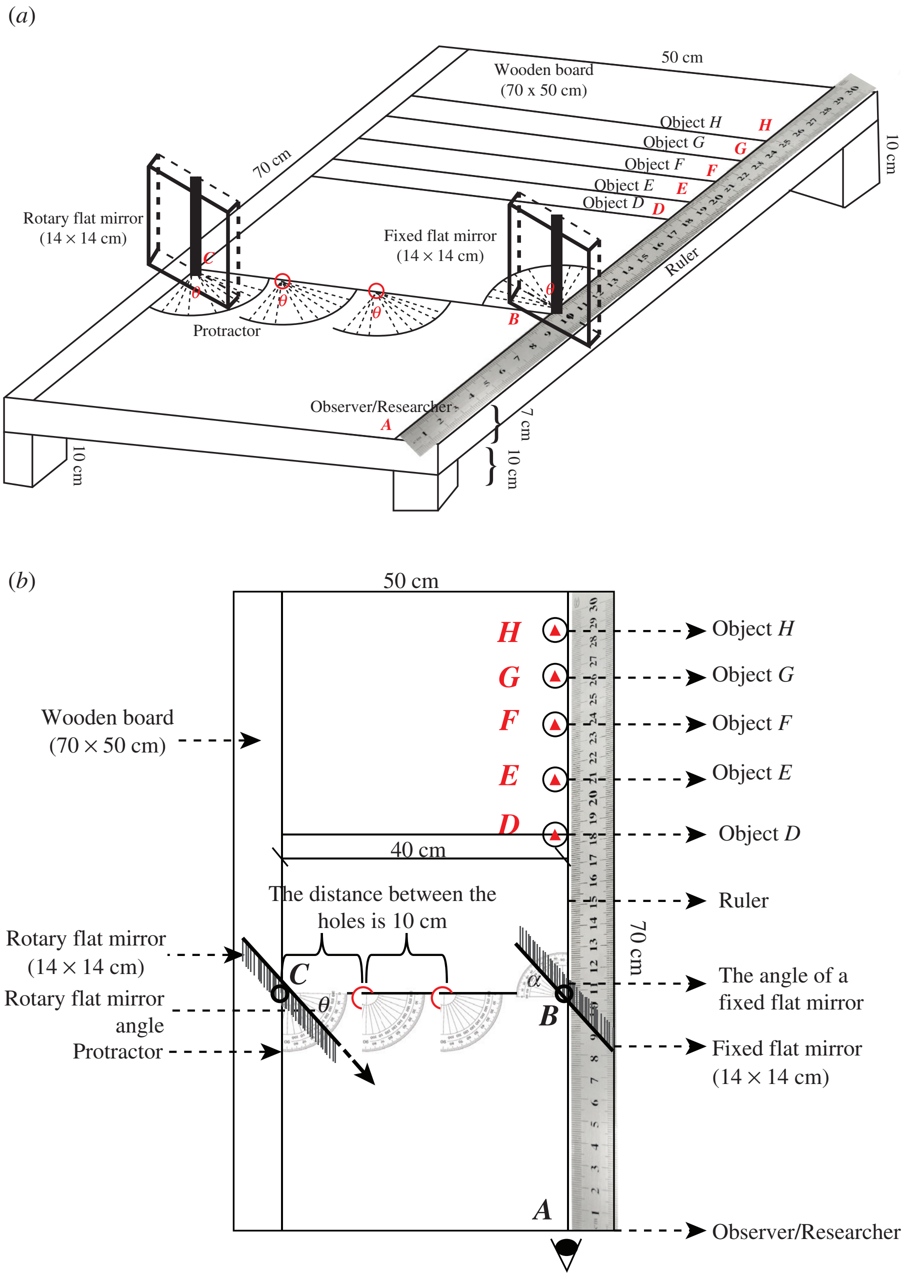

Figure 2. The design of the modified instrument by applying the law of light reflection, i.e: (a) three dimensions (3D) and (b) top views.

instrument. The design of the modified distance-measuring instrument can be observed in figure 2.

The second stage is to construct the (modified) distance-measuring instrument. This stage consists of (i) preparing the tools and materials based on the design of figure 2, and (ii) constructing the measuring instrument using the tools and materials that have been prepared. This stage begins with preparing (i) four protractors, (ii) one ruler (70 cm), (iii) two flat mirrors ($14 \times 14\,\text{cm}^2$), and (iv) pieces of wood. Each protractor is cut into two parts along the 90° angle line, while the flat mirrors are sanded on the edges. The back of each flat mirror is covered with a cardboard. Next,

Figure 3. The developed measurement tool to determine the distance between two objects via the law of light reflection, i.e.: (a) top and (b) front views.

a wooden table is made as a stand for this measuring instrument. The flat mirror support is made from wood and placed onto the wooden table. Finally, the protractors and the ruler are placed on the wooden table (figure 3).

The third stage is the development of the measuring instrument that has been constructed. This stage starts with using the measuring instrument that has been built and correcting the shortcomings (errors) found on the measuring instrument. Then, re-using again the instrument that has been modified in accordance with the design and the law of light reflecting. Finally, the measuring instrument is tested. The result of the developed measuring instrument can be observed in figure 3.

The working principle of this distance-measuring instrument can be presented in figure 4. Based on figure 4, consider the object to be measured is located at point G and measured (by an observer) at point A. The rotary and fixed flat mirrors are located at point C and B, respectively, on the measuring instrument. The light path starts from point G (the location of the object) and goes to point C (the roratry flat mirror) then reflected back to point B (fixed flat mirror) according to the light reflection law, and finaly reflected to an observer at A. Thus, geometric relations are obtained as follows:

$$AG = AB + BG. \tag{1}$$

Setting $AB = BC$, then equation (1) becomes

$$AG = BC + BG. \tag{2}$$

On the other hand, according to figure 4, we also have

$$BG = BC\,(\tan(180 - 2\theta))\,. \tag{3}$$

Substituting equation (2) into equation (3) produces:

$$AG = BC\,(1 + \tan(180 - 2\theta))\,. \tag{4}$$

where AG is the distance between the two objects (cm), BC is the distance between the two flat mirrors (cm), θ is the angle of the rotary flat mirror (°), and α is the angle of the fixed flat mirror. Equation (4) is used to measure the distance between two objects in this study.

The procedure to measure the distance between two objects using this instrument can be explained as follows: (i) arranging the tools and materials according to the design in figure 2, (ii) placing the object to be measured on the wooden

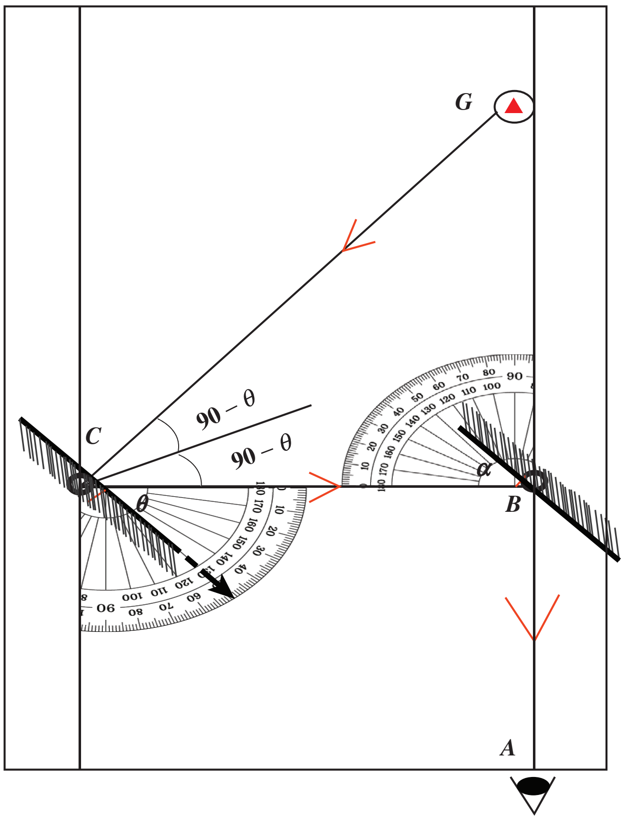

Figure 4. The geometric illustration of a ray of light passing through the distance-measuring instrument based on the law of light reflection.

table according to figure 2, (iii) measuring the distance between the two flat mirrors, (iv) positioning the observer at point A (figure 4), (v) setting α to 25°, (vi) rotating the rotary flat mirror until the image of the object is visible on the fixed flat mirror, (vii) determining θ, (viii) using equation (4) to determine the distance of object (from point A), (ix) repeating the distance measurement of the object five times, and (x) repeating steps (vi) to (ix) with variation of α at 30° and 45°. We also vary the distance of the rotary flat mirror from the fixed flat mirror, i.e.: 40 cm, 30 cm, and 20 cm, and repeat procedure (i) to (x) for each distance. Finally, for a comparisan purpose, the distance of the object (AG) is also measured using a ruler.

The data obtained are analyzed using averaging, i.e.:

$$\overline{AG} = \frac{\sum_{i=1}^{n} AG_i}{n}, \tag{5}$$

with $\overline{AG}$ is the average distance (cm) and $\sum_{i=1}^{n} AG_i$ is the sum of lengths of AG from $i = 1$ to the nth measurements.

Finally, the precision and accuracy of the measurement results are determined using standard deviation and relative uncertainty equations, respectively. These are given as follows:

$$\Delta AG = \sqrt{\frac{\sum_{i=1}^{n} \left(AG_i - \overline{AG}\right)^2}{n-1}}, \tag{6}$$

with ΔAG is the standard deviation of the object's distance (cm), and

$$KR = \left(\frac{|X - Y|}{Y}\right) \times 100\%, \tag{7}$$

with KR is the relative uncertainty (%), X is the measured distance using the instrument (cm), and Y is the measured distance using a ruler (cm).

3. Results and discussion

The first result of the first study is the development of the design and construction of the distance measuring instrument based on the law of light reflection. This design is developed based on deficiencies and limitations found in the distance measuring instrument that had been developed in [13]. The shortcomings contain in the previous instrument include (i) the limitation on the minimum and maximum distance measurements, viz.: 20 cm and 50 cm, respectively, (ii) the spatial limitation to rotate the flat mirror (fixed at 45°), and (iii) the limitation of the number of objects being measured (three objects). In addition, the dimension of the previous measuring instrument is $50 \times 30\,\text{cm}^2$ with the dimension of the flat mirror is $10 \times 10\,\text{cm}^2$, which only has one fixed distance between the flat mirrors of 20 cm. The results obtained for the relative uncertainty and the standard deviation of the distance measurements are quite large, namely 2.39% and 2.37%, respectively [13].

Therefore, the distance-measuring instrument in this study is an improvement of the previous measuring instrument. The improvement made is not only in the specifications of the measuring instrument, but also on the tools and materials used, as well as the design of the measuring instrument. The modification upon the measuring instrument includes (i) the range of the instrument is increased from 15 cm to 70 cm, (ii) the flat mirrors can be rotated, and (iii) the number of object being measured is increased to five points. Furthermore, the measuring instrument developed in this study has a dimension of $70 \times 50\,\text{cm}^2$ and supported by wooden legs. The flat mirror dimension is $14 \times 14\,\text{cm}^2$ with three variations of the distance between the two flat mirrors, viz.: 20 cm, 30 cm, and 40 cm. In this study, we show the distance measurement results by varying α, i.e.: 25°, 30°, 45°, and 60°. The design modification of the distance-measuring instrument between two objects is shown in figure 2.

The results of the distance measurements using the instrument and a ruler can be observed in table 1. Based on table 1, there are five positions of the objects being measured from the farthest to the nearest with respect to A, i.e.: H to D. In general, it can be observed that the results of the measurements from the instrument are in accordance with the ruler measurements. This means that the instrument is valid to measure the distance of an object. However, different α for the same θ gives different distance results. One way to analyze these differences is to look at the accuracy obtained for each α, that is 98.17%, 98.01%, and 97.87% for 45°, 30°, and 25°, respectively. It can be observed that the lowest relative uncertainty is obtained for α of 45°, i.e.: 1.83%, which means that 98.17% of the distance measurements are in accordance with the ruler measurements. This means that the best accuracy of the distance measurement using the instrument is obtained when α is at 45°. This is because at the time of measurement, the observer is in a straight line with the image (shadow) of the object being measured on the fixed flat mirror. Moreover, the precision of the measuring instrument is provided from the average standard deviation in the last column of table 1. It may be observed that all of the average standard deviation of the measuring instrument is smaller than the standard deviation of the previous instrument (2.37%), which means that the precision of the present instrument has been improved.

Moreover, in order to determine the measurement range of the instrument, we first set α to 60°. The result obtained is that the distance of the five objects (D to H) cannot be measured. This is because the observer must shift to the left, hence not in-line with the image of the object. This is a limitation of the measuring instrument that it cannot measure the distance when α is equal to or larger than 60°. Therefore, the maximum measuring distance of an object is able to be measured if α is 45°. To find the minimum angle that may be used to measure the distance, the fixed flat mirror is set to 25°, which may be obsered in table 1. Reducing further he fixed flat mirror angle to 20° does not produce an image of the object as the observer has to shift to the right. Therefore, the minimum measuring distance of an object is obtained when α is 25°. Finally, we obtain the measurement range of the instrument in term of α, i.e.: 25° to 45°.

Equation (4), which is the basis for calculating the distance of an object is further analyzed. It is obvious that the aforementioned equation is quite simple as it only depends upon θ and not on α. Hence, varying α should not affect the distance of the object for the same θ. Of course we

Table 1. Results of the distance measurement using the measuring instrument (and the ruler).

		Distance between the flat mirrors (*BC*)								
		40 cm		30 cm		20 cm				
α	Position of the object	Distance measured (cm)	Standard deviation (cm)	Distance measured (cm)	Standard deviation(cm)	Distance measured (cm)	Standard deviation(cm)	Distance measured using a ruler (cm)	Average distance measured using the instrument (cm)	Average standard deviation (cm)
45°	*H*	65.41	1.63	64.78	1.33	66.75	2.51	65	65.65	1.82
	G	60.56	0.96	60.23	1.15	59.65	1.86	60	60.15	1.33
	F	55.20	0.88	54.85	1.49	53.59	1.44	55	54.55	1.27
	E	50.57	0.82	50.86	0.85	49.23	0.95	50	50.22	0.87
	D	45.05	0.78	45.16	0.72	44.89	0.96	45	45.03	0.82
Relative uncertainty = 1.83%										
30°	*H*	65.03	1.95	64.78	1.33	65.05	3.01	65	64.95	2.09
	G	59.88	1.90	59.81	1.15	59.65	1.86	60	59.78	1.64
	F	54.89	1.32	54.85	1.49	54.71	1.98	55	54.82	1.60
	E	49.98	1.49	49.95	1.27	49.70	1.59	50	49.88	1.45
	D	45.05	0.78	44.90	1.09	44.89	0.96	45	44.95	0.94
Relative uncertainty = 1.99%										
25°	*H*	66.19	1.09	66.32	1.53	65.05	3.01	65	65.85	1.87
	G	60.21	0.96	60.23	1.15	60.33	1.52	60	60.26	1.21
	F	55.20	0.88	55.19	1.26	55.83	1.63	55	55.41	1.26
	E	50.28	1.24	50.25	1.08	50.12	1.06	50	50.22	1.13
	D	45.63	1.76	45.16	0.72	45.28	1.53	45	45.36	1.34
Relative uncertainty = 2.13%										

may also modify the equation so it may incorporate α. However, we do not further discuss this here and may be left as an exercise for students or as future studies. Moreover, some limiting cases may be deduced from equation (4) with fixing α at 45°. It may be observed that θ has a range of 0° to 90°, i.e.: $0° \leqslant \theta \leqslant 90°$. This produces $0 \leqslant \tan\,(180 - 2\theta) < \infty$(i.e.: positive values) for $90° \geqslant \theta > 45°$, and $-\infty \leqslant \tan\,(180 - 2\theta) < 0$ (negative values) for $45° > \theta \geqslant 0°$, where ∞ is infinity. Hence, the range that produces a physical meaning of the distance is $90° \geqslant \theta > 45°$. this means that the rotary flat mirror may only be used in the range of 45° to 90°. For $\theta \to 90°$, then $AG \to BC$, which obviously means that the object tends to get closer to point B. Next, for $\theta \to 45°$, $AG \to \infty$, which indicates that the object is located further away (at infinity) from the observer. This means that, in principle although impractical, the measuring instrument may be able to measure distant objects, as long as the objects are big enough or their images may be captured by the rotary flat mirror. However, at a range of $0° \leqslant \theta < 45°$, equation (4) breaks down and makes no sense upon the measuring instrument. Further complication arises if α is incorporated into equation (4) as previously mentioned.

This measuring instrument may be used as a Physics teaching aid for middle or high school students especially in the topics of Optics and subtopic of the light reflection law. Using this instrument, students may experience a basic application of the light reflection law in accordance with the theoretical concept given to them. This is supported by Hirca [17] that Physics instrument used in an hands on physics experiment may increase students' science process skills. To make it more interesting, after a teacher has describe the concept of the light reflection law, this instrument may be used as a hands-on demonstration apparatus for students to exercise the light reflection law. The teacher might give a task for students to conduct a distance measurement of an object located on the measuring instrument with the procedure given in the previous section and compare the result with the measurement made by a ruler. The teacher might then ask the students to make a simple version of table 1 and discuss the measurement procedure of the instrument. Moreover, students may be asked to compare the measurement procedure of the instrument and the ruler, and should find an obvious conclusion that a ruler is easier to use. On the other hand, the teacher may use this measuring instrument as a basic model to explain more complex applications of optics, e.g.: in astronomy and surveying, that may not be conducted simply using a ruler.

Finally, it is hoped that by using this measuring instrument students may understand and be more interested in the application of trigonometry and light reflection law, e.g. in astronomy. This measuring instrument may be used as a physics teaching aid in middle or high schools, especially to study and demonstrate the working principles of simple telescopes. This is because this instrument is used to measure the distance of not too distant objects with limitations given by the light reflection law and trigonometry. Moreover, we argue that the working principle of this measuring instrument is similar to that of a general telescope, especially in observing the light path from the object to the observer through optical mirrors.

4. Conclusions

An instrument to measure the distance between two objects by applying the law of light reflection is designed and constructed using simple, inexpensive, and easily obtained tools and materials. The results of the distance measurements of the objects are in good agreement with the results obtained using a ruler for all variation of α from 25° to 45°. Moreover, this measuring instrument can be used as a physics teaching aid in optics, especially to show a basic application of the light reflection law. Students may be given the tasks to (i) conduct the measurement done in this study, (ii) improve the measuring instrument itself, and (iii) improve the equation used. Further studies in improving this measuring instrument may be conducted by replacing the usual protractor with a vernier protactor to increase the accuracy of the instrument. Furthermore, it is also interesting to modify equation (4) to incorporate α.

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