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Development of AURIS (Atwood Ultrasonic Inertia System) as an Arduino-based Atwood's machine practical tool

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Abstract. This research aims to develop AURIS (Atwood Ultrasonic Inertia System) as an Arduino-based Atwood's machine practical tool with an automatic time measurement system using ultrasonic sensors. Manual time measurement on conventional Atwood's machines is prone to errors due to human response limitations. This research uses an experimental method with a design and build approach. AURIS consists of an Atwood machine, an Arduino Uno, an ultrasonic sensor, an electromagnet as an initial load holder, and an LCD as a data display. The testing was conducted with variations in load travel distance from 0.50–0.95 m, with constant masses $M_1 = 0.05$ kg and $M_2 = 0.10$ kg. Time data is used to calculate the acceleration and moment of inertia of the system. The results show a travel time of 1.21–1.66 s with a relatively constant acceleration of 0.610–0.725 m/s². The moment of inertia values range from 0.137–0.163 kg·m² with a relative error of 5.4% or an accuracy of 94.6%. The linear relationship between distance and the square of time indicates the characteristics of uniformly accelerated linear motion. AURIS is suitable for use as a practical tool for studying motion dynamics and Newton's Second Law of Physics.

Keywords: Atwood machine, Arduino, ultrasonic sensor, moment of inertia

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INTRODUCTION

Physics learning emphasizes not only the mastery of theoretical concepts but also the process of discovery through experimental activities. Through hands-on practical work, students can directly observe physical phenomena, thereby building a more meaningful understanding of concepts (Jen et al., 2023). Nugraha et al. (2017) assert that experimental physics learning is capable of developing students' conceptual understanding as well as their scientific and analytical thinking skills.

One of the experimental tools used in learning motion dynamics is Atwood's machine, which serves to study the relationship between force, mass, velocity, acceleration, and the characteristics of uniform motion (GLB) and uniformly accelerated motion (GLBB). However, Nugraha et al. (2017) stated that measuring motion parameters on Atwood's machine is still dominated by manual methods using a ruler and stopwatch, so the measurement results are highly dependent on the user's accuracy and tend to be less accurate. Atwood's machine was chosen as the object of development because its simple, low-cost, and open mechanical design allows both translational motion (acceleration, Newton's Second Law) and rotational quantities (the moment of inertia of the pulley) to be studied simultaneously within a single apparatus, making it well suited for automation with low-cost microcontroller-based sensors such as Arduino. The issue of manual time measurement was also raised by Jefiza and Novianas (2020), who stated that using a manual stopwatch often leads to errors due to human response limitations. These error impact the accuracy of speed and acceleration calculations, necessitating innovation in laboratory equipment with a more precise time measurement system.

Various development efforts have been made to improve the accuracy of measurements on Atwood's machine. Nugraha et al. (2017) developed an Atwood's machine experiment based on the Tracker application, which produced more accurate motion data, although it still required additional equipment and advanced analysis. Additionally, Jefiza and Novianas (2020) developed an automatic time measurement system based on LDR sensors, which showed a higher success rate in measurement compared to manual methods, while Elias, Makahinda, and Lolowang (2022) reported that an Arduino-based automatic timer was able to significantly reduce time measurement errors. More recently, sensor-based approaches have continued to evolve: Wheatland et al. (2021) used a smartphone’s built-in sensors as a free-rotation laboratory to measure rotational quantities without dedicated external hardware, Chen et al. (2023) refined Atwood’s-machine-based measurements of gravitational acceleration by explicitly accounting for pulley moment of inertia and bearing friction, and Jen et al. (2023) reported the use of Arduino-based instructional media to analyze kinematics quantities in the classroom.Although these prior studies have improved the accuracy of time measurement on Atwood's machines, practical tools that determine the moment of inertia of the system using an integrated automatic time measurement system remain limited. Moreover, the use of ultrasonic sensors as a non-contact load-position detector integrated with a microcontroller is still rarely implemented in this context.

Therefore, this research aims to develop AURIS (Atwood Ultrasonic Inertia System) as an Arduino-based Atwood's machine practical tool equipped with an ultrasonic sensor as an automatic time measurement system. The development of AURIS is expected to improve the accuracy of motion time measurement and support the learning of motion dynamics and Newton's Second Law more accurately and innovatively.

METHOD

This research is an experimental study with a design and build approach (experimental research and instrumentation) aimed at developing and testing the performance of the Atwood Ultrasonic Inertia System (AURIS) as an Arduino-based Atwood's machine practical tool. AURIS is designed as an automatic time measurement system that utilizes ultrasonic sensors to detect the position of the weights as they move. A diagram of the AURIS system showing the relationship between the main components is shown in Figure 1.

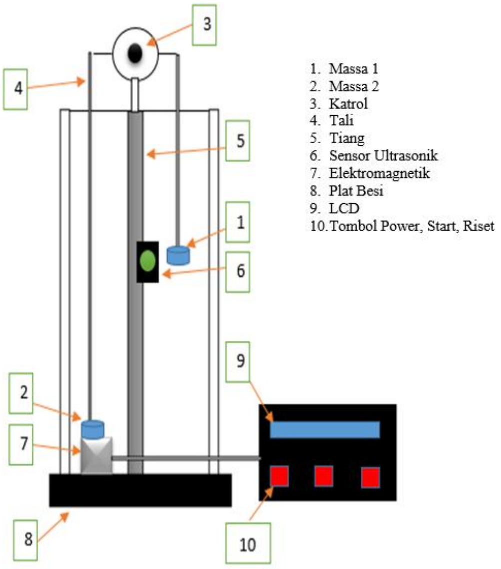

Figure 1. Automatic Atwood's Machine Design Scheme

The AURIS system consists of an Atwood machine including a pulley, rope, and slotted weights, an Arduino Uno microcontroller as the main controller, an ultrasonic sensor for detecting the position of the weight, an electromagnet as the initial weight holder, and a 16×2 LCD as a time data display. The physical form and component arrangement of AURIS as an Atwood machine practicum tool are shown in Figure 2.

Figure 2. Physical form and component arrangement of AURIS

In the initial condition, one of the weights is held by the electromagnet, so the initial position of the weight is always the same in each experiment.

When the system is activated, the Arduino cuts off the current to the electromagnet, causing the load to start moving and the timing process to begin automatically. The ultrasonic sensor detects the final position of the load at a predetermined distance and sends a signal to the Arduino to stop the timing. The measured time data is then processed by the Arduino and displayed on the LCD screen. This system is designed to minimize measurement errors caused by human response delays, which are common when using a manual stopwatch. The complete operating sequence of AURIS, from system activation to data logging, is summarized as a flow chart in Figure 3.

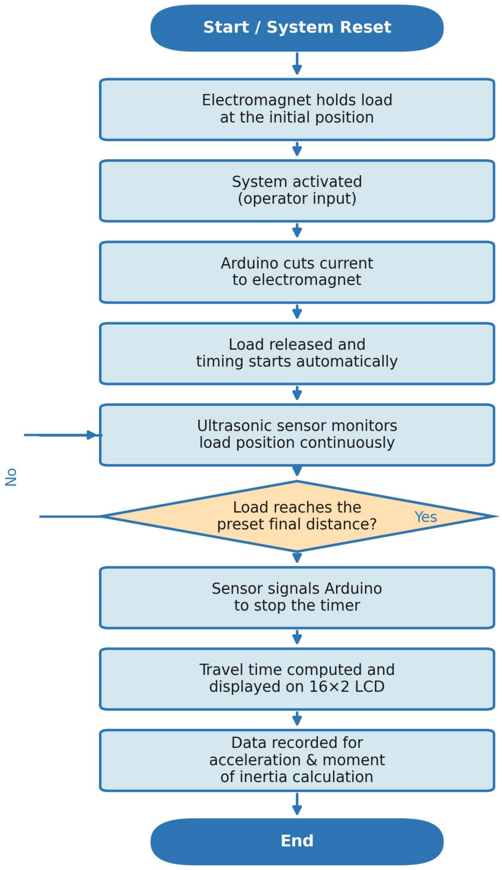

Figure 3. Flow chart of the AURIS automatic measurement procedure

The experiment was conducted by determining the mass of the load and the distance traveled by the load in an Atwood's machine system. Time measurements were taken automatically using AURIS and repeated ten times for each distance variation to obtain consistent data. The data obtained, which is the travel time of the load, is used to calculate the acceleration of motion and the moment of inertia of the system based on the equations of uniformly varied linear motion and Newton's Second Law. Data analysis is performed by determining the average value of the measurement results and calculating the relative error to evaluate the accuracy and performance of AURIS as a physics practicum tool.

RESULT AND DISCUSSION

Performance testing of AURIS was conducted by measuring the travel time of the load on the Atwood's machine system for distance variations between 0.50 – 0.95 m, with the load mass remaining constant at $M_1 = 0.05$ kg and $M_2 = 0.10$ kg. Time measurements were taken automatically using an ultrasonic sensor integrated with Arduino. The measurement results for time, acceleration, and moment of inertia of the Atwood's machine system are summarized in Table 1.

Table 1. Results of Time, Acceleration, and Moment of Inertia Measurements

No	D (m)	M_1 (kg)	M_2 (kg)	t (s)	a (m/s^2)	I (kg.m^2)
1	0,50	0,05	0,10	1,21	0,684	0,146
2	0,55	0,05	0,10	1,26	0,696	0,143
3	0,60	0,05	0,10	1,34	0,670	0,149
4	0,65	0,05	0,10	1,46	0,610	0,163
5	0,70	0,05	0,10	1,47	0,648	0,154
6	0,75	0,05	0,10	1,49	0,675	0,148
7	0,80	0,05	0,10	1,55	0,720	0,138
8	0,85	0,05	0,10	1,58	0,682	0,146
9	0,90	0,05	0,10	1,62	0,687	0,145
10	0,95	0,05	0,10	1,66	0,725	0,137

Based on Table 1, it was found that travel time for the load increased with increasing travel distance. The average time value falls within the range of 1.21 – 1.66 s. This increase in time indicates a consistent system response to distance changes, suggesting that AURIS is able to stably detect the beginning and end of load movement for each distance variation.

The acceleration values calculated from the time data are in the range of 0.610 – 0.725 m/s^2. Although the distance traveled was varied, the acceleration values obtained were relatively constant and fluctuated within a narrow range. This indicates that the Atwood's machine system tested meets the characteristics of uniform linear motion, and also reflects the consistency of the time measurement results produced by AURIS.

Based on this acceleration value, the moment of inertia of the pulley system was calculated, and the moment of inertia value was obtained in the range of 0.137 – 0.163 kg.m^2. The relatively stable moment of inertia value for each distance variation indicates that the measurement system used is capable of producing consistent data, so the calculation of the moment of inertia is not significantly affected by changes in the load's travel distance.

The relationship between the distance traveled and the square of the time of the load's movement is shown in Figure 4. The graph indicates a linear relationship between distance and the square of time, suggesting that the load's movement in the Atwood's machine system follows the characteristics of uniformly accelerated linear motion

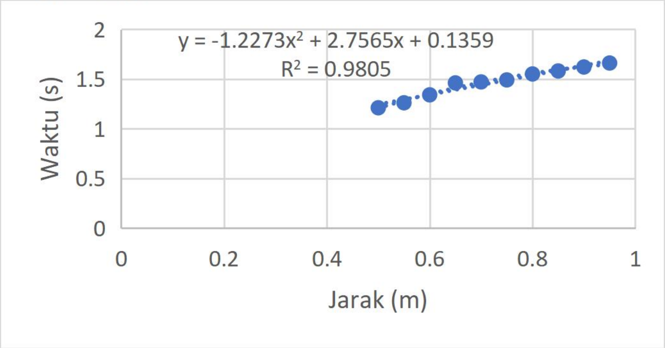

Figure 4. Graph of the relationship between distance traveled (D) and the square of time (t^2) in the AURIS system.

The linearity of this graph reinforces the acceleration calculation results obtained from the experimental data. Note that, because the load starts from rest under constant acceleration, distance and time are related quadratically as $D = ½at^2$; plotting D directly against t therefore produces a curved (quadratic) trace, whereas plotting D against t^2 – as done in Figure 4 – linearizes this relationship, with the slope of the resulting straight line equal to a/2. This is why Figure 4 shows a linear, not quadratic, trend.

Discussion

The research results show that AURIS is capable of automatically measuring the movement time of the load with good consistency. The relatively narrow range of acceleration values despite varying the distance traveled indicates that the ultrasonic sensor-based time measurement system is capable of minimizing errors due to human response delays. This finding aligns with the research results of Jefiza and Novianas (2020) as well as Elias, Makahinda, and Lolowang (2022), which state that an automated measurement system based on sensors and microcontrollers can improve the accuracy of Atwood's machine experimental results.

The experimental moment of inertia values, ranging from 0.137 to 0.163 kg.m², indicate the stability of the measurement results. A relative error of 5.4% in the measurement results indicates that the AURIS device has an accuracy level of 94.6%. The observed value differences may be caused by friction on the pulley shaft, non-uniformity of the rope mass, and limitations in the resolution of the ultrasonic sensor. Nevertheless, these results indicate that AURIS is suitable for use as a practical tool for analyzing rotational dynamics. This level of accuracy is broadly comparable to other low-cost, sensor-assisted Atwood's-machine studies reported in the literature. For instance, Chen et al. (2023) showed that explicitly accounting for pulley moment of inertia and bearing friction substantially improved the accuracy of Atwood's-machine-based measurements relative to idealized calculations, while smartphone-sensor-based approaches such as those of Monteiro et al. (2015) and Wheatland et al. (2021) have been reported to achieve comparable or somewhat lower uncertainties owing to their higher sensor sampling rates. This suggests that, while AURIS provides a clear accuracy improvement over manual stopwatch-based timing (Jefiza & Novianas, 2020), there remains room to further reduce measurement uncertainty by increasing sensor sampling rate and correcting for pulley friction, as noted above.

The graph showing the relationship between distance and the square of time, which indicates a linear trend, reinforces the agreement between the experimental results and the theory of uniformly accelerated linear motion. This finding supports the statement by Nugraha et al. (2017) that using technology-based laboratory tools can clarify motion characteristics and improve students' understanding of physics concepts. Thus, AURIS not only serves as a measuring tool but also as an effective learning medium in supporting the study of motion dynamics and Newton's Second Law.

CONCLUSION

AURIS (Atwood Ultrasonic Inertia System) was successfully developed as an Arduino-based Atwood's machine practical tool with an automatic time measurement system. This tool is capable of increasing measurement accuracy and minimizing errors caused by using a manual stopwatch. With an accuracy level of 94.6%, AURIS is suitable for use as a practicum medium to support the learning of motion dynamics and Newton's Second Law.

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