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Development of a Data Acquisition System for the Determination of the Moment of Inertia of a Flywheel

M Fernando and KP Wijayaratna*
Department of Physics, University of Colombo, Colombo 03, Sri Lanka
*kanishka_p_w@yahoo.co.uk**

ABSTRACT

This paper presents the details of construction and implementation of an automated data acquisition (DAQ) system for an undergraduate laboratory experimental setup that is intended to measure the moment of inertia of a flywheel (without disassembling the setup), using the falling mass method. The developed DAQ system is a microcontroller-based system which has facilities to calculate a value for the moment of inertia of the flywheel directly, using the acquired data.It employs optical sensors to detect the position of a known mass attached to one end of a string wound around the flywheel axel, count the number of turns made by the flywheel before releasing the mass and after releasing the mass and measure the time taken for the mass to fall through a known distance.Measurements were taken under nine different conditions by changing the mass and its fall-through height with both manually operated and automated experimental setup. The average of the measured values of the moment of inertia of the flywheel under the two operation modes are found to be $\overline{I}_{\text{manual}} = 0.348 \pm 0.005 \text{ kg m}^2$ (without taking inherent personal errors of the manual operation mode into account)and $\overline{I}_{\text{auto}} = 0.315 \pm 0.005 \text{ kg m}^2$.It is also seen that $\overline{I}_{\text{auto}}$ agrees with the directly calculated value of the moment of inertia of the flywheel, $I_{\text{direct}} = 0.302 \pm 0.020 \text{ kg m}^2$ within their experimental uncertainties, indicating that the reliability of the data taken with the automated system is higher.

1.0 INTRODUCTION

Human related errors (for example, response time of the experimenter) play an important role when carrying out laboratory experiments manually. In situations where two or three manual measurements are needed to be taken simultaneously, it becomes a laborious task to perform. In such cases, the human related errors become large and as a result, the reliability of the collected data becomes low.

The experimental setup available in the physics laboratory for undergraduates at the Department of Physics, University of Colombo, to determine the moment of inertia of a flywheel is a system thatrequirestaking several measurements simultaneously while the flywheel is turning around.This experimental setup consists of a heavy metal disc having physical parameters as, radius ~ 0.15 m, thickness~ 0.06 m, axle diameter ~ 0.03 m and mass ~ 27 kg.However, collecting data with minimum error with this setup has become a difficult task, especially for a single undergraduate. This difficulty is mostly due to the manual data taking process, a task that essentially requires the involvement of two undergraduates. Although it is possible to assign two undergraduates for taking readings, their response times never synchronise with each other and the problem still remains the same.

System automation is the best option that can be used to overcome the drawbacks in the existing setup. With the application of computers, software, transducers, data acquisition hardware, signal conditioning hardware and mechanical systems, system automation has been used extensively in many different fields over the past few decades. The main objective of this research work was to automate the existing experimental setup to make the experiment more efficient and to take the data with a higher accuracy by reducing some personnel errors involved in the experiment and also, making it possible for a single person to carry out the data taking.

2.0 METHODOLOGY

2.1 Experimental setup andmethodology

A flywheel of standard pattern is available with a mount to be fixed on to a table or a wall. A mass attached to a length of a fine cord which is wrapped around the axle and the free end being passed through a hole in the axle. The length of cord is adjusted so that when the attached mass reaches the ground, the cord detaches itself from the axle[1,2].As shown in Fig. 1, the mass m is allowed to fall through a measured distance s to the ground.

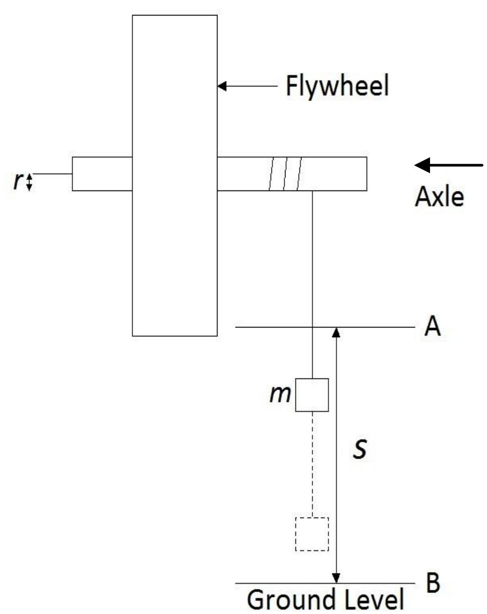

Fig. 1: Experimental setup

The required measurements for the calculation of the moment of inertia are: the time of descent (t), the number of revolutions (n) of the wheel during this time, further revolutions (N) made by the wheel before coming to rest after the mass m is detached, fall through distance (s) and radius (r) of the axle of the flywheel to which the mass m is attached. Devices used for taking these measurements in the manual operation and automated operation are as listed in Table 1.

Table 1: Devices used to take the required measurements

Measurement [SI Unit]	Manual Operation	Automated Operation
m [kg]	Electronic balance	Electronic balance
s [m]	Meter ruler	Meter ruler
r [m]	VernierCalliper	VernierCalliper
t [s]	Digital stop watch	Timer function of the microcontroller
n revs.	Observation of a mark made on the circumference of the wheel	Optical encoder and motion detector
N revs.	Observation of a mark made on the circumference of the wheel	Optical encoder and motion detector
Displaying collected data	-	LCD display and seven segment display

It can be shown[1] that, the moment of inertia of the flywheel is given by the following relation

$$I = mr^2\left(\frac{gt^2}{2s} - 1\right)\left(\frac{N}{N+n}\right) \quad \text{..(1)}$$

2.2 Data acquisition

2.2.1 Optical encoder

In this work, an optical encoder was constructed using a LM324 IC[3], an IR LED and a ST1KLA phototransistor[4] and, it was used to measure the number of turns made by the flywheel under two different conditions as described above. LM324 is an Op-Amp IC and in this case, the Op-Amp was used as a comparator.As shown in Fig. 2 and 3, an encoding optical pattern was painted along the circumference of the flywheel disc. Then, an infrared beam emitted from an IR LED was made to incidence on the encoding pattern and the reflected beam was collected by a photo transistor. Depending on the intensity of the reflected beam, the voltage at the emitter should be varied and this varying voltage was used to switch the comparator by comparing with a reference voltage. For a white surface, the intensity of the reflected beam will be high and for a black surface, it will be very low.

The output of the comparator was supplied to the RB0 I/O pin of the PIC 16F877A[5] and by using a suitable programme, the number of pulses made by the comparator was counted by means of pulse counters during time of descent of the attached mass and before the wheel coming to rest after releasing the mass. The outputs of these pulse counters were then used to calculate the number of revolutions made by the flywheel during the above two cases of rotation.

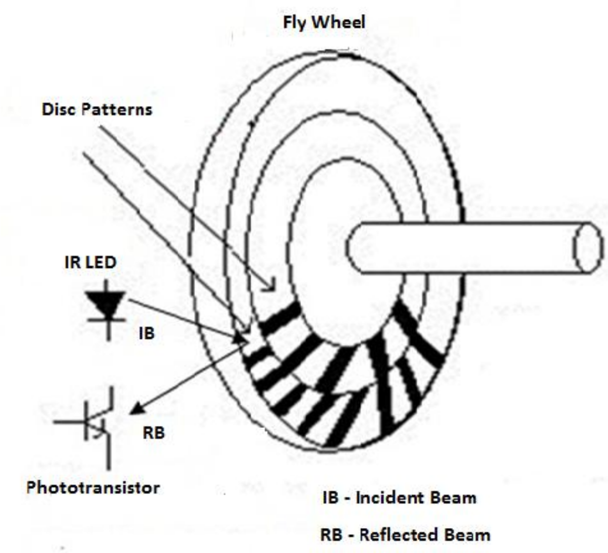

Fig. 2: Position of the emitter and detector

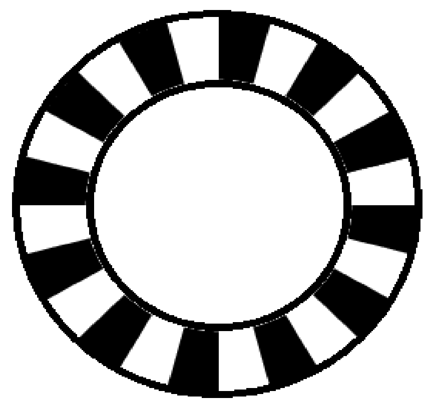

Fig. 3: The optical encoding pattern

2.2.2 Motion detector

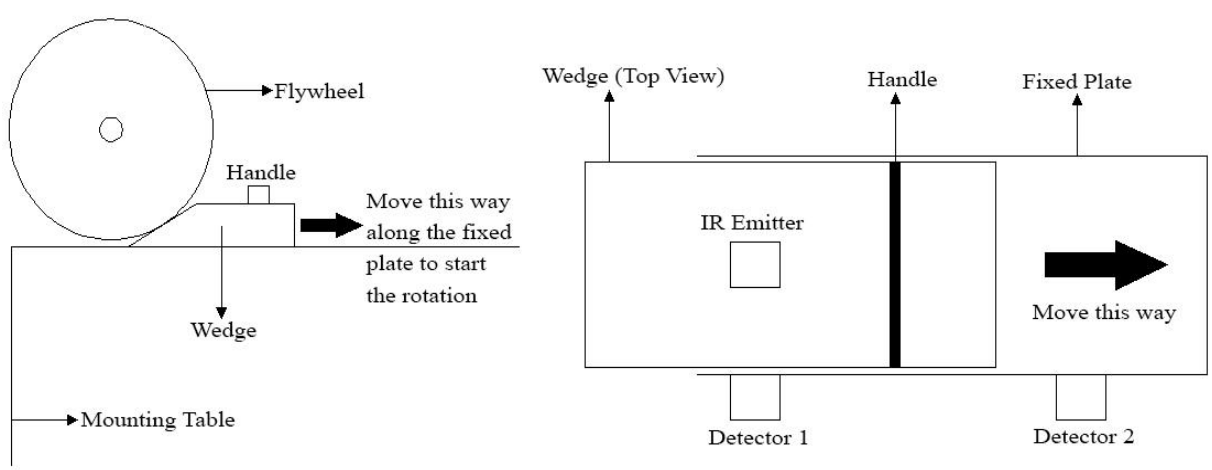

Fig. 4: Schematic diagram of the setup used for detecting the motion at Position1

In this work, motion detectors are used at two different positions. The two detectors are used to detect the start of the rotational motion (Position 1) of the flywheel and to detect the time at which the mass reaches at the ground (Position 2). In this case, some parts especially constructed for this purpose were used in conjunction with the detectors. Fig. 4 shows the mechanical system used at Position 1 and it consists of two identical IR detectors and one IR emitter as in the above mentioned optical encoder.

Soon after a reasonable size mass is attached to the axle of the flywheel, it begins to turn and as a result, it becomes difficult to make any measurements. Therefore, it is essential to keep the flywheel not turningaround until other measuring devices are ready. To achieve this situation, a wedge-shaped object was used to apply some friction on the flywheel and thereby to prevent it from turning. The same wedge was used to mount the motion detectors and to start the rotation of the flywheel, the wedge should be pulled to the right along the fixed plate. When the flywheel is in the fixed (non-turning) position, the IR emitter and Detector 1 are aligned and when the emitter is moved away, the change of voltage of Detector 1 will feed a signal to the microcontroller to inform that the rotation has begun and the timer should be switched on. Triggering of the timer is programmed so that it occurs at a falling edge of the incoming signal pulse. So, once the emitter is aligned with Detector 2, it should be switched on to create a rising edge of the pulse to be fed to the microcontroller and this should be done before the mass touches the ground.

Fig. 5 shows a schematic diagram of the setup used for detecting the motion at Position 2 which is set at the ground level. In this diagram, Position A corresponds to a state where the mass is very close to reach the ground and the Position B corresponds to a state where the mass has reached the ground. At Position A, the IR beam is not blocked by the mass and at Position B, the beam is blocked by the mass. This change in state is used to provide the second falling edge signal that can be used for the timer to be switched off and to let the optical encoder know that the mass has reached the ground and then the pulse counter should be triggered to the second stage (To count the number of pulses made after reaching the ground).

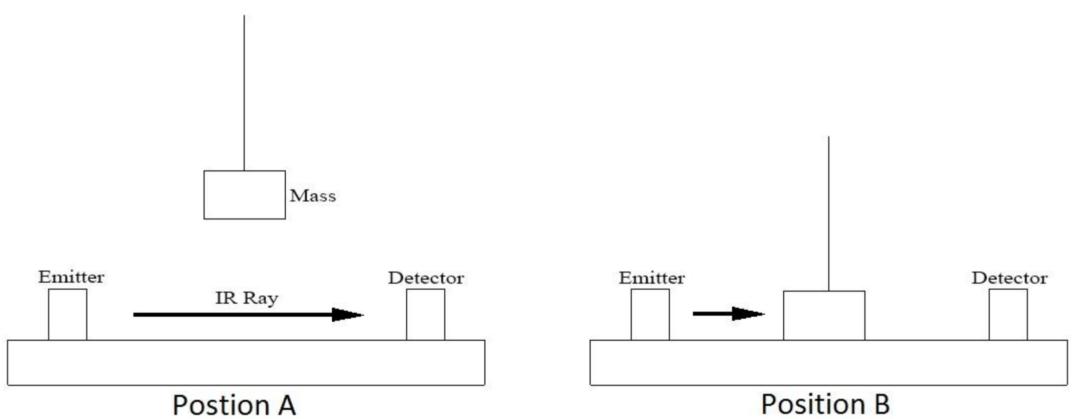

Fig. 5: Schematic diagram of the setup used for detecting the motion at Position 2

2.2.3 Function of the microcontroller

Two PIC microcontrollers (16F877A- 40 pin DIP Package) have been used in this work to execute two different tasks. One is to display the data coming from the two pulse counters and to display the results through a LCD display. When the data acquisition is over, this unit could be used to calculate the moment of inertia of the flywheel according to the user inputs given. The other microcontroller is used to display the time taken for the mass to reach the ground level starting from its initial position. In this case it is required to operate the microcontroller as a real-time counter and in order to achieve this state, Timer 0 module[5] of the PIC microcontroller is used and it is displayed on a 4-digit seven segment display.

3.0 RESULTS AND DISCUSSION

Data were collected for 03 different masses and for 03 different heights by keeping all other parameters constant. Three measurements of the moment of inertia were obtained for a particular set of values of mass and height and, their average value was calculated as follows[6].

$$I_{\text{avg}} = \left(I_1 + I_2 + I_3\right)/3 \quad \text{..........(2)}$$

Since there were only 03 values of moment of inertia to take the average, the uncertainty associated with the I_{avg} value was obtained as follows.

$$\delta I_{\text{avg}} = \frac{1}{3}\sqrt{\left((\delta I_1)^2 + (\delta I_2)^2 + (\delta I_3)^2\right)} \quad \text{..........(3)}$$

The calculated values of I_{avg} and their associated uncertainties, obtained by using the data taken manually and the data acquired from the data acquisition system developed under this research project, are presented in Table 2.

Table 2: Comparison of I_{avg} values and their associated uncertainties in the two methods

Settings of mass and height	$I_{\text{avg}} \pm \delta I_{\text{avg}}$ (kg m^2) (Calculated usingdata taken manually)	$I_{\text{avg}} \pm \delta I_{\text{avg}}$ (kg m^2) (Calculated using data acquired from DAQ system)
m =0.50 kg, s=0.70 m	0.340 ± 0.010	0.323 ± 0.004
m = 0.50 kg, s=0.80 m	0.344 ± 0.009	0.307 ± 0.004
m =0.50 kg, s=0.90 m	0.345 ± 0.001	0.316 ± 0.003
m =0.55kg, s=0.70 m	0.348 ± 0.001	0.321 ± 0.007
m =0.55kg, s=0.80 m	0.346 ± 0.002	0.311 ± 0.008
m =0.55kg, s=0.90 m	0.351 ± 0.005	0.315 ± 0.006
m =0.60 kg, s=0.70 m	0.366 ± 0.005	0.316 ± 0.004
m =0.60 kg,s=0.80 m	0.351 ± 0.005	0.310 ± 0.003
m =0.60 kg, s=0.90 m	0.342 ± 0.003	0.318 ± 0.003

Percentage uncertainties of data (in Table 2) obtained from the manual system and the automated system,vary from 0.5% to 4.5% and from 0.5% to 2.5% respectively. The average value and the uncertainty of all 09 measured values of the moment of inertia of the flywheel obtained from the manually operated and automated setup are as given below.

$$\bar{I}_{\text{manual}} = 0.348 \pm 0.005 \text{ kg m}^2 \text{ (Percentage uncertainty 1.4 \%)}$$

$$\bar{I}_{\text{auto}} = 0.315 \pm 0.005 \text{ kg m}^2 \text{ (Percentage uncertainty 1.6 \%)}$$

Here it should be mentioned that, as there are 09 values obtained in each mode of operation, the standard deviation of these 09 values has been taken as the uncertainty of each $\bar{I}_{\text{manual}}$ and $\bar{I}_{\text{auto}}$ values.

This DAQ system works better for small masses when operated at a low height and, this can be understood as follows. Since the height and the mass are small, the torque exerted by the mass on the wheel and the linear acceleration of the system are not very high. So, the frequency of incoming signals to the counters can be kept at a low level and this will in turn increase the reliability of the results yielded by the system. Here it is important for the distance between the optical encoder and the flywheel to be small because,the optical encoder requires a sufficient intensity for the incoming signal to have in order to be able to detect it. It should be mentioned that, this DAQ system does not give a unique result for the same settings as it depends highly on the way that the mechanics of the setup behaves.

As mentioned before, the flywheelin the experimental setup was a heavy metal disc having physical parameters: radius = 0.15 m and mass = 26.8 kg, which could be measured only after dismantling the experimental setup. However, due to the fact that the axle rod of the flywheel had been attached permanently to the wheel at its centre so that the rod is sticking out of the flat faces of the wheel, it was impossible to measure the radius of the wheel directly. So, the circumference of the wheel had to be measured with a non-stretching string and then, the radius had to be calculated. Also, the mass of the wheel was relatively large and it had to be measured with a weight measuring scale used to measure the body weight at the university medical centre. These measuring techniques could have resulted in relatively large uncertainties in the measured values of radius and mass and, the respective uncertainties could be quoted reasonably as 0.005 m and 0.1 kg. In order to check whether the values we obtained for $\bar{I}_{\text{auto}}$ and $\bar{I}_{\text{manual}}$ are reasonably accurate for the flywheel used, a crude direct value for the moment of inertia was calculated by using the formula $I = \frac{1}{2}MR^2$, where M is the mass and R is the radius of the flywheel. (Here it should be noted that, when calculating the direct value of the moment of inertia by means of the above formula, the mass of the axle rod has been included in the mass of the flywheel, however the fact that it is sticking out of the flat sides of the flywheel at the centre has not been considered. However, this contribution of the axle to the moment of inertia of the flywheel could be considered as a small percentage.) This value is found to be $I_{\text{direct}} = 0.302 \pm 0.020 \text{ kg m}^2$ (with a percentage uncertainty of 6.6 %, due to large uncertainties in the measured values of M and R). By comparison of results obtained from all three methods it is clear that the value of the moment of inertia of the flywheel determined for the automated system, $\bar{I}_{\text{auto}}$ agrees with the I_{direct} value within itslarge experimental uncertainty quoted. Due to the unavoidable personal errors involved in the manually operated set up, a significant difference can be seen between the values of $\bar{I}_{\text{manual}}$ and I_{direct} within the experimental uncertainties quoted.

4.0 CONCLUSIONS

System automation can be incorporated to manually-operated experimental setups mainly for the purpose of reducing errors that occur in the data taking process and not solely for the purpose of operation of the setup in a user-friendly manner.The automated DAQ system described in this report is a combination of microcontroller (PIC), optical (IR) sensors and display units. The microcontroller is the main device which collects data from the external devices connected to it and then, calculates and displays the results according to the user's requirements.Both manually-operated and automated setups involve some common systematic uncertainties such as those due to environmental factors. However, the uncertainty that is introduced due to the user's performance does not play a major role in the automated setup.

As shown by the results obtained, the manually-operated system (with its inherent personal errors not taken into account) and the automated system have yielded results which are in agreement within the experimental uncertainties quoted.The constructed DAQ system in this project work has the capability of providing trusted, efficient measurements for the moment of inertia of a flywheel. Finally, it should be mentioned that, with present-day technology incorporated to a conventional experimental setup, students will find it more interesting to do an old conventional experiment with the new automated setup.

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