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Comparison of friction coefficient of static and sliding determination methods: conventional, video tracking and IoT-based

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ABSTRACT

The prevalent physics parameter in the concepts of friction are the friction coefficient of static and sliding. The objective of this research is to determine the friction coefficient of static and sliding by means of conventional measurement, video-tracking as well as proposed IoT-based measurement likewise to compare the results of each methods correspondingly theoretical references. Two universal systems in determining friction coefficient of static and sliding are reproduced, involves both conventional and IoT-based measuring instruments: flat block against flat runway and flat block against inclined runway. Video-tracking is the most precise between conventional and IoT-based method as its %RSD mean value of interval reading and angle of inclination respectively 6.22% and 0.88%. In case determination of friction coefficient of static three methods have equal %TE mean value of 22.85% for oak-based block on cast iron plank excluded slightly 0.49% of differences than assumed %TE value of video-tracking. Each methods are considerably accurate since each friction coefficient of sliding are theoretical values required range of 0.300 – 0.500. for oak-based block on cast iron plank IoT-based measurement has the smallest mean value of %TE indicating most accurate between two other methods.

Keywords: friction coefficient of sliding; friction coefficient of static; IoT; sensors; video tracking

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INTRODUCTION

The prevalent physics parameter in the concepts of friction are the friction coefficient of static and sliding, both of which be evidence of the roughness of two surfaces in contact. Two universal systems in determining these coefficients are as illustrated in Figure 1 (Prastyo dkk, 2021; Yuliani dkk, 20). Friction coefficient of static prevails if a mass is not moving relative to the surface and opposes any would-be motion whilst friction coefficient of sliding (in many cases called friction coefficient of kinetic) is taken into account if a mass is moving (has a non-zero velocity) relative to the surface and opposes that motion.

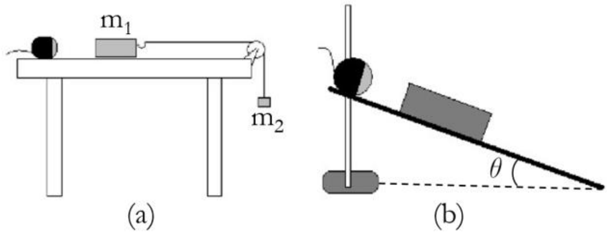


Figure 1. Two universal systems in determining friction coefficient of static and sliding: (a) flat block against flat runway; (b) flat block against inclined unway

In Fig. 1(a), the friction coefficient of static μ_s is given by:

$$\mu_s = \frac{m_2}{m_1} \tag{1}$$

Where $\mathbf{m_1}$ and $\mathbf{m_2}$ are respectively mass of the object on the flat plane (in kg) and minimum mass of weighting applied to move $\mathbf{m_1}$ (in kg)
Meanwhile, in Fig. 1(b) the friction coefficient of static μ_s could be written:

$$\mu_s = \tan \boldsymbol{\theta} \tag{2}$$

Where $\boldsymbol{\theta}$ stands for critical angle of inclination applied to move the object on the inclined plane. On the other hand, in Fig. 1(a) the friction coefficient of sliding μ_k is given by:

$$\mu_k = \frac{m_2 - \frac{2d}{gt^2}(m_1 + m_2)}{m_1} \tag{3}$$

where $\mathbf{m_1}$, d, t are respectively the mass (in kg), object displacement (in m) and time interval (in s) for which the object slides on the flat plane as well as $\mathbf{m_2}$ stands for mass of weighting applied to move $\mathbf{m_1}$ (in kg) nd g is 10 m/s^2.

Meanwhile, in Fig. 1(b) the friction coefficient of the sliding μ_k could be written:

$$\mu_k = \tan \boldsymbol{\theta} - \frac{2d}{gt^2} \cdot \frac{1}{\cos\theta} \tag{4}$$

where $\boldsymbol{\theta}$, d, t are respectively the angle of inclination (in degree), object displacement (in m) and time interval (in s) for which the object slides on the inclined plane and g is 10 m/s^2.

Conventionally, friction coefficient of static and sliding determination entails analog and/or digital stopwatch and analog protractor for measuring time interval and angle of inclination respectively. Nevertheless, a short track which the object slides on the flat and/or inclined plan leads to time reading errors (Andriani et al., 2021; Humairo et al., 2018) and discrepancies of friction coefficient of static and sliding in consequence. Furthermore, as a result parallax errors of analog protractor could affect the friction coefficient of static and sliding. One of improvement investigated considers video-tracking to measure friction coefficient of static and sliding (Haris & Lizelwati, 2016; Humairo et al., 2018; Tacenca et al., 2021). This indirect measurement utilizes video-tracking based observation (Febriyana et al., 2022) and tracks some set of video frames (Tacenca et al., 2021), hereafter obtaining an accurate and valid of the friction coefficient of static and sliding (Humairo et al., 2018).

Lamentably, video-tracking encounters some challenges such as the resolution or the frame per second (fps) number of recorder (Andriani et al., 2021) as well as tracking reference point (Febriyana et al., 2022). Additionally, the video-tracking constrains offline-mode of the friction coefficient of static and sliding as prior we should analyze some extracted physics parameters. Considering such adversities that is convenient to introduce sufficient sensor-microcontroller linkage of which integrated with internet of things (IoT). IoT emphasizes on transformation process (Aldowah et al., 2017) in interdisciplinary aspects of science, technology, engineering and mathematics (STEM) of which the implementation contriving a real-time cyber-physical system bolstered by ubiquitous sensors (Aldowah et al., 2017), unique identified devices (Fathurrahmaniah et al., 2021; Pongoh et al., 2022) as well as data exchange and communication through sustainable network.

Previous studies has been unveiled the friction coefficient of static and sliding by utilizing sensor-microcontroller linkage (Manuhutu et al., 2023; Yuliani et al., 2024). Despite the absence of studies of IoT application determining the friction coefficient of static and sliding, IoT has been promoted to design a physics props of Newton's Second Law (Muchlis et al., 2018), to detect the oscillation of the spring-mass system (Irwandi et al., 2020), to develop a thermodynamics law experiment media (Liana et al., 2020)), to design IoT-based real laboratory of thermal expansion (Ramadhani, 2021) as well as to design IoT-based real laboratory of Newton's Law of Cooling (Mutaqin, 2021).

The objective of this research is to determine the friction coefficient of static and sliding by means of conventional measurement, video-tracking as well as proposed IoT-based measurement likewise to compare the results of each methods correspondingly theoretical references.

RESEARCH METHODS

Each systems of Fig. 1(a) and 1(b) are reproduced as shown in Fig. (2), involves both conventional and IoT-based measuring instruments: flat block against flat runway and flat block against inclined runway.

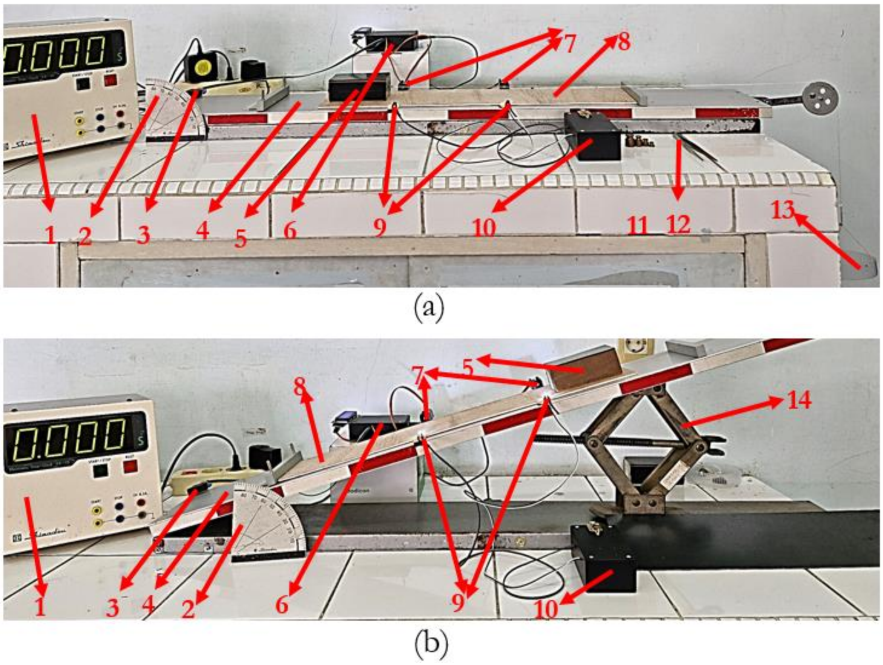
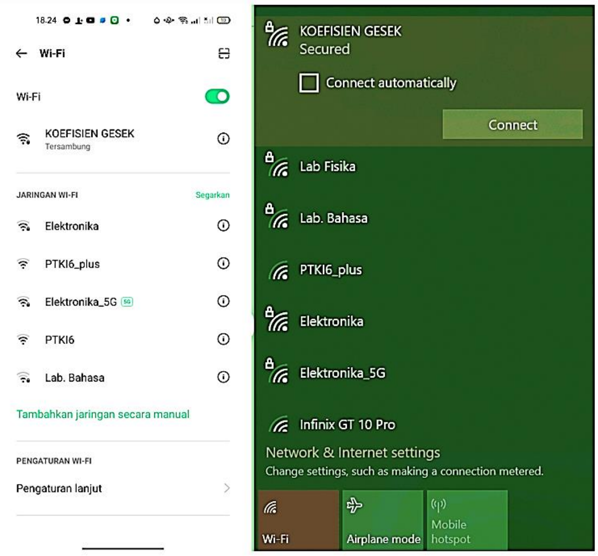


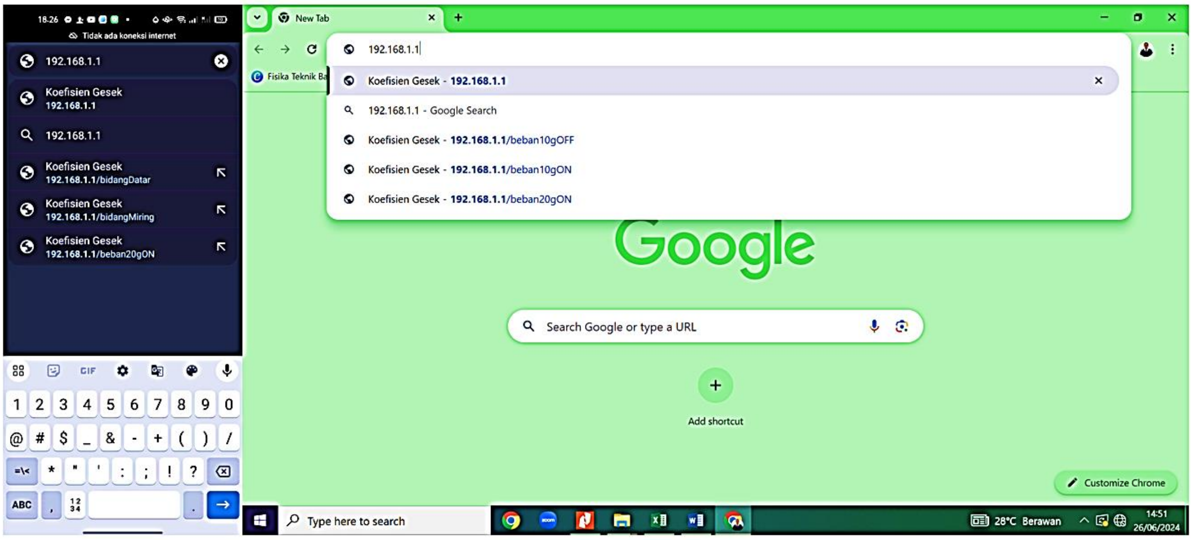
Figure 2. Two reproduced systems in determining friction coefficient of static and sliding: (a) flat block against flat runway; (b) flat block against inclined runway

Mechanical and electronic parts are numbered as following: (1) digital stopwatch; (2) analog protractor; (3) angle sensor i.e. MPU6050 accelerometer; (4) sliding apparatus equipped with pulley; (5) 0.1177-kg oak-based flat block; (6) IoT devices circuit box comprises of ESP32 NodeMCU, connected sensors as well as embedded liquid crystal display (LCD); (7) time interval sensor i.e. two light dependent resistors (LDRs) mounted 2 cm away each other; (8) two (53.2 x 12.0)-cm optionally sliding planks each made of oak and cast iron; (9) two light emitting diodes (LEDs) mounted 2 cm away each other and facing each LDRs; (10) LEDs charger; (11) various weights of 0.002, 0.005, 0.01, 0.02, 0,05, 0.1 and 0.2 kg; (12) tweezer as weights transporting media; (13) 0.0089-kg weights container threaded to oak-based flat block; (14) scissor jack as angle of inclination adjuster.

Separate from mechanical and electronic parts the video recording-tracking equipment as well as the IoT-based data displays involve two smartphones (one as video recording device and one for IoT-based data display) and a laptop for IoT-based data display likewise as video tracking device (with 6.1.0 version video tracker software installed). Video recording smartphone adjusted on landscape position, maximum rate of 60 fps, full high definition (FHD) as well as 9:16 aspect ratio. IoT-based data display is achievable due to bridging of IoT devices, application programming interfaces (API) as well as online services. The implementation of this concept is a unique wireless networking (wi-fi) address labelled “Koefisien Gesek” established as shown in Fig. 3(a) and reciprocally exclusive access to a local webserver as shown in Fig. 3(b).



(a)



(b)

Figure 3. IoT-based Data Display: (a) Unique wi-fi address (left: smartphone, right: laptop); (b) Local Webserver (left: smartphone, right: laptop)

The experiments are completed by running each system of Fig. 2(a) and Fig. 2(b) to measure essential quantities of time interval and angle of inclination, on the other hand each mass values have already specified above. Respectively each system operates once applied available either variation mass of weighting (include minimum mass) or variation angle of inclination (include critical angle). Furthermore both systems employ contact surfaces of oak-based flat block on the cast iron sliding planks as well as oak-based flat block on the oak sliding planks. The mechanism of measurement of time interval and angle of inclination along with video recording are as following: (1) wi-fi is connected to laptop/smartphone and local webserver initiates; (2) video recording starts; (3) wooden block slides and passes respectively 1st and 2nd LDRs; (3) digital stopwatch displays time interval reading and angle of inclination must be measured manually meanwhile simultaneously IoT-Based measurement equipment performs as shown in Fig. 4; (4) video recording stops.

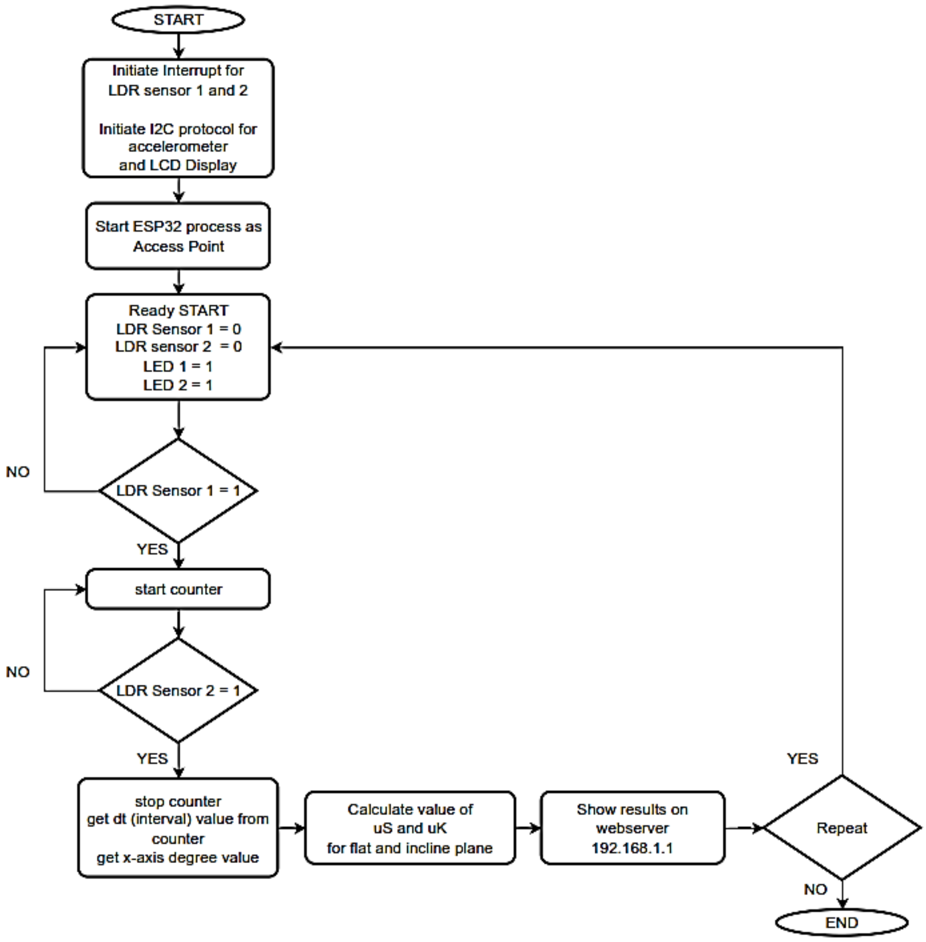


Figure 4. Flowchart of IoT-based measurement equipment

In the system in Fig. 2(a) for each wood-wood and wood-iron contact surfaces, prior is investigated the minimum mass of weighting by assigning available following order of variations: 0.002kg, 0.005kg, 0.01kg, 0.02kg, (0.02 + 0.005) kg, (0.02 + 0.005 + 0.002) kg, (0.02 + 0.01) kg. Momentarily the wooden block slides the minimum mass of weighting value which are respectively (0.02 + 0.01) kg and (0.03 + 0.02) kg for wood-wood contact surface and wood-iron contact surface are manually recorded. Hereinafter, each five attempts assigning the minimum mass of weighting are observed in order to convince the precision of time interval sensor. Eventually, for wood-wood contact surface three angles of inclination are investigated which are (0.02 + 0.01 +0.002) kg, (0.02 + 0.01 + 0.005) kg, (0.02 + 0.01 + 0.005 + 0.002) kg, and for wood-iron contact surface three angles of inclination are investigated which are (0.03 + 0.02 +0.002) kg, (0.03 + 0.02 + 0.005) kg, (0.03 + 0.02 + 0.005 + 0.002) kg. Entire time interval and angle of inclination readings are recorded manually. There are to be convinced that on the local web-server page it is selected only one value of each assigned mass of weighting and press “Refresh” before switching to another value. For instance “2”, “10 and “20” are selected represents (0.02 + 0.01 +0.002) kg. Entire time interval and angle of inclination readings are recorded manually.

In the system in Fig. 2(b) for each wood-wood and wood-iron contact surfaces, prior is investigated the critical angle of inclination by adjusting following order of variations: 20°, 21°, 22°, 23°, 24°, 25°, 26°, 27°, 28°. Momentarily the wooden block slides the critical angle of inclination values obtained which are respectively 23° and 26° for wood-wood contact surface and wood-iron contact surface are manually recorded. Hereinafter, each five attempts assigning the critical angle of inclination are observed in order to convince the precision of time interval sensor as well as angle sensor. Eventually, for wood-wood contact surface three angles of inclination are investigated which are 24°, 25°, 26°, and for wood-iron contact surface three angles of inclination are investigated which are 29°, 30°, 31°. Entire time interval and angle of inclination readings are recorded manually.

Video tracker features only support tracking time interval and angle of inclination, as one of video-tracking sample is shown in Fig. 5. Entire time interval and angle of inclination tracings are recorded manually.

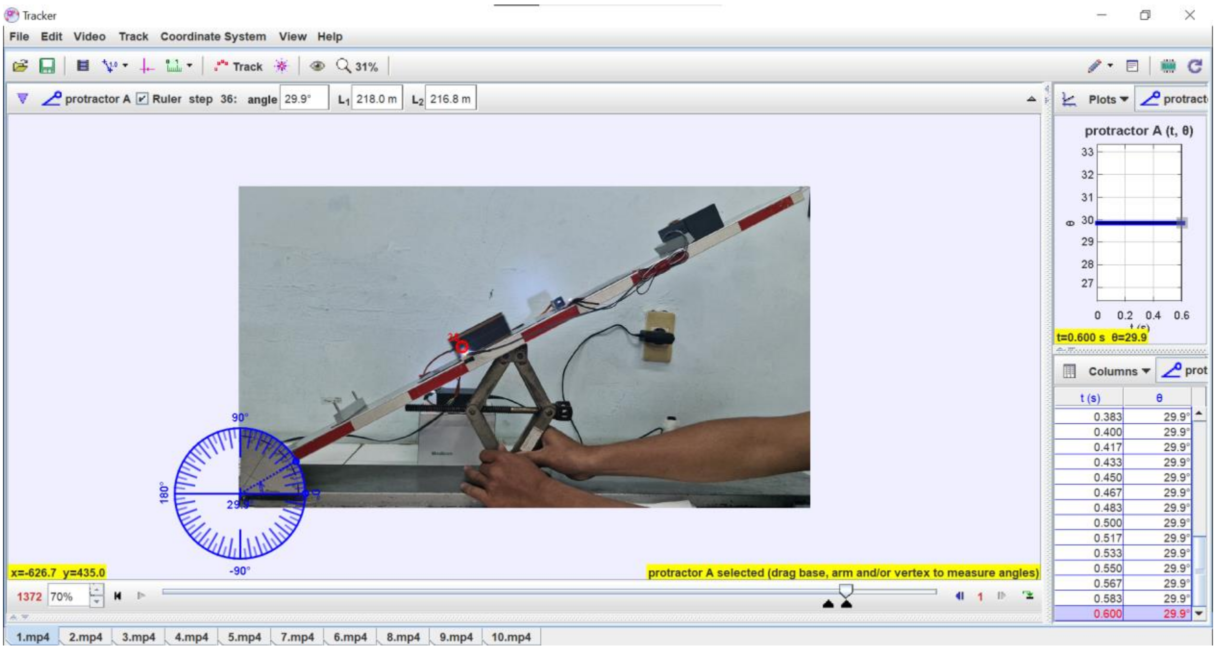


Figure 5. Video-tracking sample

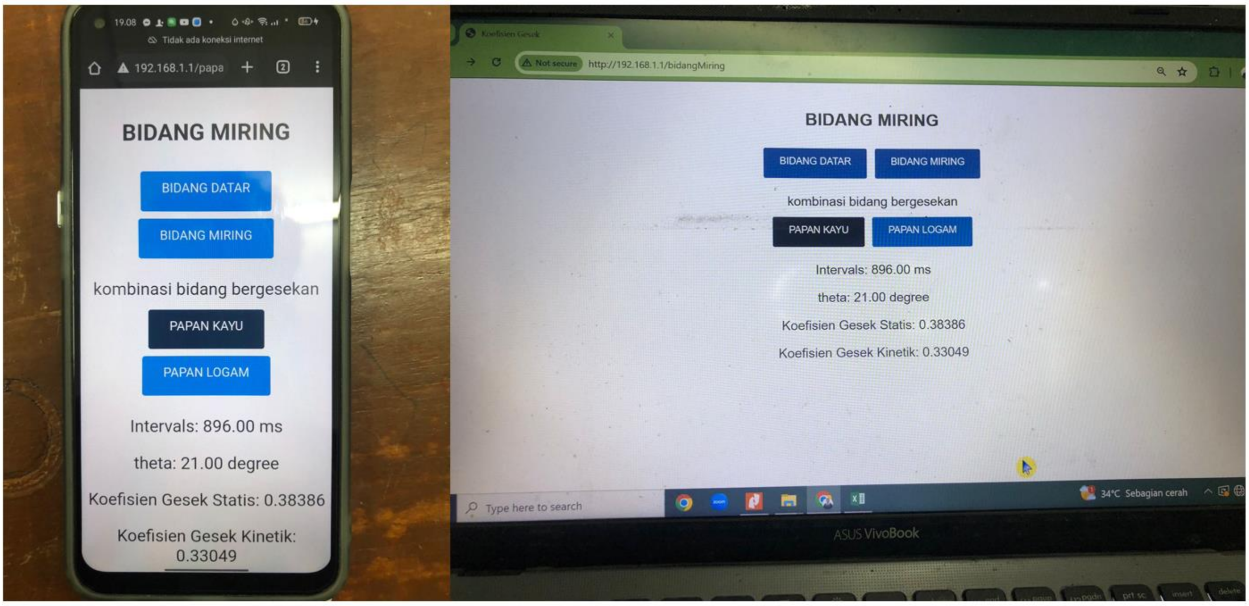
As for conventional method, refer to Eq. (1) and (2) friction coefficient of static are calculated respectively for minimum mass of weighting value obtained i.e. (0.02 + 0.01) kg as well as the critical angle of inclination values obtained i.e. 23° and 26°. Meanwhile refer to Eq. (3) and (4) friction coefficient of sliding are calculated for entire time interval and angle of inclination readings of each systems Fig. 1 and Fig. 2.

A statistical approach to convince precision of the time interval sensor as well as the angle sensor is relative standard deviation percentage (%RSD), moreover % RSD is computed for conventional measurement tools as well as video-tracked time interval and angle of inclination. As a result, it is unveiled comparison of measurement precision of conventional, video tracking and IoT-based.

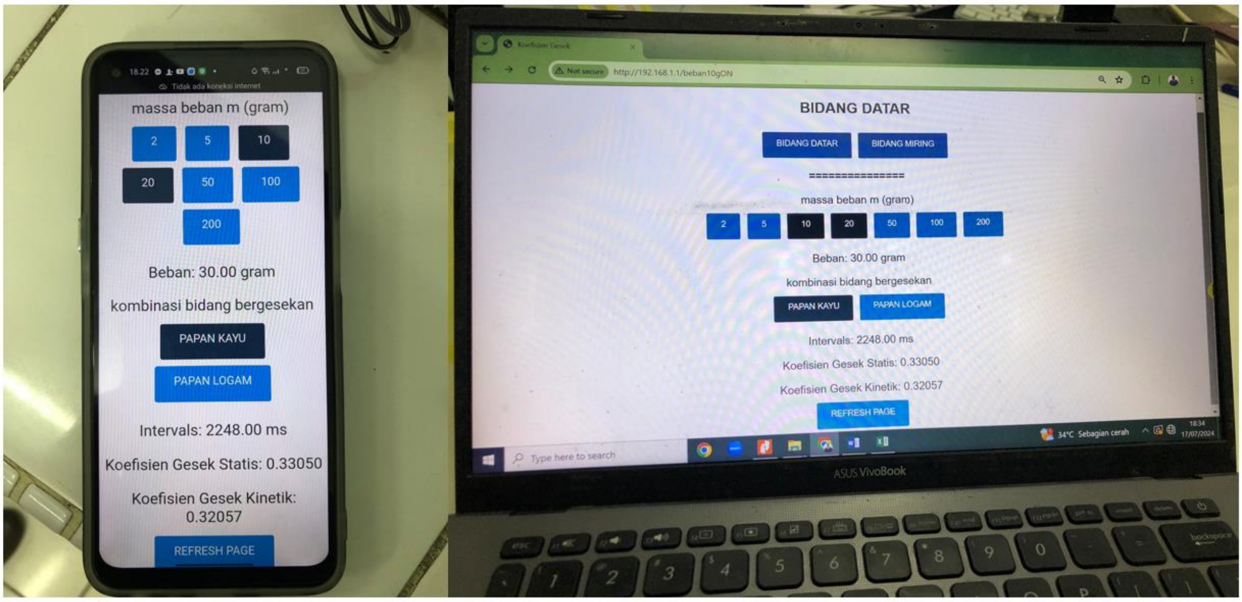
Theoretical values of friction coefficient of static and sliding have been classified and are universal for all friction coefficient of static and sliding methods involve flat block against flat runway and flat block against inclined runway. The theoretical values are respectively friction coefficient of static and sliding of oak on oak are of 0.610 and 0.320 meanwhile friction coefficient of static and sliding of cast iron on oak are of 0.485 and range of 0.300 – 0.500. The comparison of friction coefficient of static and sliding determination methods of the three methods is demonstrated by theoretical error percentage (%TE). This validates the differences between any observed value and the theoretical value as percentages. Final confident outcome is as minimum as %TE of IoT-based compared to two other methods.

RESULTS AND DISCUSSION

For instance, Fig. 6 delineates the proposed IoT-based measurement readings.



(a)



(b)

(c)

Figure 6. IoT-based measurement readings: (a) Inclined plane (left: smartphone, right: laptop); (a) Flat plane (left: smartphone, right: laptop); (c) LCD display

Followings are English translation of every script of Fig. 6(a) and 6(b): 1) bidang datar = flat plane; 2) bidang miring = inclined plane; 3) papan kayu = oak plank; 4) papan besi = cast iron plank; 5) massa beban = mass of weighting; 6) beban = mass variation of weighting; 7) koefisien gesek statis = friction coefficient of static; 8) koefisien gesek kinetik = friction coefficient of sliding. Meanwhile, followings are meaning of every script of Fig. 6(a), 6(b) and 6(c): 1) intervals = time interval; 2) theta = angle of inclination; 3) dt = time interval; 4) a = angle of inclination; 5) s = friction coefficient of static 6) k = friction coefficient of sliding.

Table 1 shows precision test of flat block against flat runway meanwhile Table 2 represents precision test of flat block against inclined runway.

Table 1. Precision test of flat block against flat runway

Contact Surface	Minimum Mass of Weighing (kg)	Attempt	Time Interval (s)		
			Conventional	IoT-Based	Video Track
Oak-based block on cast iron plank	0.03	1st	0,968	1,023	0,967
		2nd	0,913	1,043	0,967
		3rd	0,959	1,026	0,983
		4th	0,986	1,076	1,017
		5th	0,985	1,096	1,017
Oak-based block on oak plank	0.05	1st	1,268	1,246	1,383
		2nd	1,221	1,22	1,217
		3rd	1,239	1,268	1,317
		4th	1,372	1,237	1,167
		5th	1,339	1,256	1,167

Table 2. Precision test of flat block against inclined runway

Contact Surface	Attempt	Time Interval (s)			Critical Angle of Inclination (^{O})		
		Conventional	IoT-Based	Video Track	Conventional	IoT-Based	Video Track
Oak-based block on cast iron plank	1st	0.699	0.751	0.717	28	28	27.7
	2nd	0.313	0.598	0.683	28	28	27.8
	3rd	0.308	0.620	0.683	28	28	28.0
	4th	0.705	0.690	0.667	28	28	28.0
	5th	0.658	0.540	0.683	28	28	27.8
Oak-based block on oak plank	1st	0.432	0.587	0.533	23	23	22.8
	2nd	0.531	0.608	0.550	23	23	23.0
	3rd	0.653	0.757	0.700	23	23	22.5
	4th	0.619	0.711	0.650	23	23	23.1
	5th	0.403	0.606	0.567	23	23	23.2

Table 3. %RSD of time interval

Contact Surfaces – System	RSD (%)		
	Conventional	IoT-Based	Video Track
Oak-based block on cast iron plank – flat block against flat runway	3.10	3.04	2.56
Oak-based block on cast iron plank – flat block against inclined runway	38.61	12.84	2.67
Oak-based block on oak plank – flat block against flat runway	5.05	1.47	7.70
Oak-based block on oak plank – flat block against inclined runway	20.93	11.54	11.95
Mean	16.92	7.22	6.22

Table 4. %RSD of angle of inclination

Contact Surfaces	RSD (%)		
	Conventional	IoT-Based	Video Track
Oak-based block on cast iron plank	0.00	0.00	1.27
Oak-based block on oak plank	0.00	0.00	0.48
Mean	0.00	0.00	0.88

Table 3 summarizes the %RSD calculation results and shows video-tracking has smallest %RSD mean value of time interval reading indicating this method is the most precise between two other methods hence it is advisable for repetitive data. The irreproducibility of IoT-based measurement in reading time intervals is that the LDRs may still receive interference from outside, even though presence of LEDs. Therefore, it could be proposed to apply other meticulous sensors such as proximity sensor or magnetic sensor. Furthermore, as shown in Table 4 %RSD mean value of angle of inclination of conventional and IoT-based is 0.00%. This is immensely obvious considering neither the analog protractor nor the MPU6050 accelerometer displays decimals, thus necessarily employment of decimal analog protractor or adjusting the potentiometer value of MPU6050 accelerometer.

Table 5 shows result of friction coefficient of static calculations meanwhile Table 6 represents result of friction coefficient of sliding calculations. %TE is not calculated on contact surfaces of oak-based block on cast iron plank either flat block against flat runway or flat block against inclined runway as the theoretical value is known in the form of a given range 0.300 – 0.500.

Table 5. Friction coefficient of static

Contact Surfaces – System	Friction coefficient of static		
	Conventional	IoT-Based	Video Track
Oak-based block on cast iron plank – flat block against flat runway	0.500	0.500	0.500
Oak-based block on cast iron plank – flat block against inclined runway	0.424	0.424	0.418
Oak-based block on oak plank – flat block against flat runway	0.331	0.331	0.331
Oak-based block on oak plank – flat block against inclined runway	0.532	0.532	0.525

Table 6. Friction coefficient of sliding

Contact Surfaces – System	Mass of Weighting or Angle of Inclination	Friction coefficient of sliding		
		Conventional	IoT-Based	Video Track
Oak-based block on cast iron plank – flat block against flat runway	0.032	0.299	0.312	0.307
	0.035	0.287	0.319	0.322
	0.037	0.263	0.308	0.307
Oak-based block on cast iron plank – flat block against inclined runway	24^{O}	0.289	0.326	0.431
	25^{O}	0.343	0.300	0.455
	26^{O}	0.311	0.356	0.474
Oak-based block on oak plank – flat block against flat runway	0.052	0.457	0.298	0.445
	0.055	0.460	0.303	0.442
	0.057	0.445	0.297	0.454
Oak-based block on oak plank – flat block against inclined runway	29^{O}	0.258	0.307	0.281
	30^{O}	0.287	0.316	0.280
	31^{O}	0.257	0.305	0,272

Table 7. %TE of friction coefficient of static

Contact Surfaces – System	Minimum Mass of Weighting or Critical Angle of Inclination	TE (%)		
		Conventional	IoT-Based	Video Track
Oak-based block on cast iron plank – flat block against flat runway	0.05 kg	31.75	31.75	31.75
Oak-based block on cast iron plank – flat block against inclined runway	28°	9.69	9.69	8.25
Mean		22.85	22.85	22.85
Oak-based block on oak plank – flat block against flat runway	0.03 kg	18.03	18.03	18.03
Oak-based block on oak plank – flat block against inclined runway	23°	30.49	30.49	31.48
Mean		24.26	24.26	24.75

As shown in Table 7, for oak-based block on cast iron plank IoT-based measurement has similar %TE to conventional method as well as assumed %TE value of video-tracking since the absence of tracking feature of mass of weighting. Further for oak-based block on oak plank IoT-based measurement has equal %TE to conventional method yet slightly 0.49% of differences than assumed %TE value of video-tracking. Nevertheless the IoT-based measurement is the most advance between two other methods as demonstrated in Fig. 6, friction coefficients of static and sliding are automatically calculated and real-time displayed although whole data has not yet electronically stored and systematically collected as a database. Alternatively, to improve IoT-based measurement of friction coefficient of static additional accelerometer attached to the flat block thus more precise of minimum masses and critical angles can be attained.

Table 8. %TE calculations of friction coefficient of sliding

Contact Surfaces – System	Mass of Weighting or Angle of Inclination	TE (%)		
		Conventional	IoT-Based	Video Track
Oak-based block on oak plank – flat block against flat runway	0.052	42.91	6.97	39.14
	0.055	43.58	5.22	38.20
	0.057	39.07	7.09	41.82
Oak-based block on oak plank – flat block against inclined runway	29^{O}	19.52	4.19	12.06
	30^{O}	10.34	1.22	12.53
	31^{O}	19.75	4.56	15.03
Mean		29.20	4.88	26.46

As shown in Table 6, each methods are considerably accurate since each friction coefficient of sliding are theoretical values required range of 0.300 – 0.500. Meanwhile Table 8 demonstrates for oak-based block on cast iron plank IoT-based measurement has the smallest mean value of %TE indicating most accurate between two other methods. It is suggested other experiment for metal-metal contact surfaces. This study indicates that static friction coefficients measured using conventional methods, IoT, and video tracking yield consistent values with minimal differences. However, the IoT-based method tends to show higher values for kinetic friction coefficients than conventional methods, especially on flat surfaces. Li et al. (2022) research on the friction coefficient between curling stones and ice using computer vision technology shows that the friction coefficient decreases with increasing friction speed, consistent with the Lozowski friction model and sensor data. Wen et al. (2022) reported that in studies of dry friction between a ball and disc, the friction coefficient initially increases and then stabilizes, with the maturation period decreasing with increasing average load and rotational speed. During the stable period, the friction coefficient is almost unaffected by surface roughness.

In this study, video tracking proved to provide the highest precision in measuring time intervals and inclination angles, with the smallest %RSD values. Conversely, IoT-based methods show good precision for kinetic friction measurements but are less accurate in time interval measurements compared to video tracking. Conventional methods, while effective, are not as accurate as video tracking and IoT methods. Sari (2019) demonstrated that using Arduino to determine the friction coefficient on an inclined plane provides consistent data and is adaptable for teaching purposes. Ciornei et al. (2017) noted that the rolling friction coefficient measurement method on an inclined plane shows increased coefficients with higher inclinations, reflecting limitations in normal load variations. Research by Kelemenová et al. (2020) highlights the challenges in measuring shear friction coefficients with variable angle tribometers, particularly the difficulties in maintaining a constant angle and the potential for errors in the measurement process, emphasizing the importance of selecting the appropriate measurement method and adjusting technology to improve data accuracy.

Additional research on ice friction by Velkavrh et al. (2019) reveals that various parameters such as ice temperature, ambient air temperature, relative humidity, relative sliding speed, and surface roughness significantly affect ice friction. Alben (2019) showed that undulatory motion in a snake with isotropic friction results in minimal net movement and proposed numerical methods to study the efficiency of various motions under Coulomb isotropic friction, finding local optima involving static friction. An analytical model by Arakawa (2017) for dynamic shear friction during impact, based on the angular velocity of a golf ball, demonstrates alignment with observed changes in angular velocity and existing empirical relationships.

Research by Vukelic et al. (2021) indicates that a new method for determining kinetic friction coefficients on an inclined plane shows increased coefficients with higher average sliding speeds and shorter sliding times. Vinogradova (2017) found that a disc on an inclined plane with dry friction stops after a specific time if the friction coefficient exceeds the incline angle, with friction and rotation ceasing simultaneously. Cross (2023) explains that the total friction force on circular objects consists of static friction and additional shear friction if the object begins to slide from the peak of the incline. Improved methods for determining rolling friction coefficients using inclined planes, as noted by Ciornei et al. (2019), emphasize the importance of accurately determining experimental parameters.

The combined results from this study and previous research highlight the necessity for selecting appropriate measurement methods and technologies for friction evaluation. Further research is needed to optimize the understanding and application of friction data under various experimental conditions. This study also contributes to understanding force concepts for students, particularly in identifying force diagrams for objects placed on inclined planes, whether stationary, moving at a constant speed, or accelerating (Sirait et al., 2018). By providing a clearer understanding of these force concepts, students can better comprehend the practical applications of friction in real-world scenarios.

CONCLUSION

Video-tracking is the most precise between conventional and IoT-based method as its %RSD mean value of interval reading and angle of inclination respectively 6.22% and 0.88%. In case determination of friction coefficient of static three methods have equal %TE mean value of 22.85% for oak-based block on cast iron plank excluded slightly 0.49% of differences than assumed %TE value of video-tracking. Each methods are considerably accurate since each friction coefficient of sliding are theoretical values required range of 0.300 – 0.500. for oak-based block on cast iron plank IoT-based measurement has the smallest mean value of %TE indicating most accurate between two other methods.

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