Investigating the Usefulness of Robots as Educational Resources in High School Science: Aiding Students to Obtain Measurement Data That Are Easy to Examine Using the Kalman Filter

Saki Taguchi, Shibaura Institute of Technology

Saki Taguchi is currently an undergraduate student in the Department of Engineering Science and Mechanics at Shibaura Institute of Technology (SIT) in Japan. Her main research is interface robots.

Kasumi Hoshino, Shibaura Institute of Technology

Kasumi Hoshino is currently an undergraduate student in the Department of Engineering Science and Mechanics at Shibaura Institute of Technology (SIT) in Japan. Her main research area is an optical lens.

Yutaro Tsuchida, Shibaura Institute of Technology

Yutaro Tsuchida is currently an undergraduate student student in the Department of Engineering Science and Mechanics at Shibaura Institute of Technology (SIT) in Japan. His main research is small robotic hands.

Sogo Fujita, Shibaura Institute of Technology

Sogo Fujita is currently an undergraduate student in the Department of Engineering Science and Mechanics at Shibaura Institute of Technology (SIT) in Japan. His main research is object detection algorithm using ultrasonic sensors.

Prof. Hatsuko Yoshikubo Ph.D., SHIBAURA INSTITUTE OF TECHNOLOGY

Dr. Hatsuko Yoshikubo obtained Ph. D. in English Literature from Chiba University in Japan in 2002. She is currently a Professor of Humanities and a senior departmental administrator, currently attached to the Innovative Global Program in the College of Engineering at Shibaura Institute of Technology, a highly-ranked engineering university in Tokyo. Innovative Global Program (IGP) is an engineering degree program incorporating humanities components, with a student body consisting mainly of international students (https://igp.shibaura-it.ac.jp).

As part of her current role as Deputy Director of the IGP, she is the Principal Investigator for the following research grants: - Japan Society for the Promotion of Science Research: Grant 24K06133 (2024-2027) - Shibaura Institute of Technology Grant for Educational Reform and Research Activity (AY2024).

Her research interests include: (1) Impacts and potential benefits of including humanities components in science and engineering degree programs (2) Innovative methods of assessment in science and engineering education, especially in the context of remote learning, hybrid courses, and collaborative international programs (3) Solving systematic issues that impact the effectiveness of science and engineering education programs, in both in-person and remote learning contexts.

In recent years she has been a presenter at the following international conferences: World Educational Research Association (WERA): WERA Conference 2019, 2022, 2023, 2024 Asia-Pacific Association for International Education (APAIE): APAIE Conference 2022, 2023, American Society for Engineering Education (ASEE): Annual Conference 2022, 2023, 2024 International Institute of Applied Informatics (IIAI): International Conference on Data Science and Institutional Research (DSIR) 2023

Awards: SIT's Presidential Award 2023 ASEE 2023: Multidisciplinary Engineering Division's 'Best Diversity Paper' Award DSIR 2021: 'Outstanding Paper' Award

Prof. Sumito Nagasawa Ph.D. in Engineering, Shibaura Institute of Technology

Prof. Dr. Sumito Nagasawa received Ph.D. in Engineering from the University of Tokyo in 2001. He is a Professor in Department of Engineering Science and Mechanics at SIT. His research interests include miniaturized robots using Micro-Electro-Mechanical Systems technologies and robot education for STEAM.

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Abstract

This study proposes a robot-based teaching tool with an integrated data acquisition and analysis support system to facilitate the understanding of motion concepts in physics education. Since sensor noise might increase cognitive load and degrade conceptual understanding, the system applies Kalman filtering for automatic data correction in the background. This allows students to interpret experimental results more intuitively, without explicit awareness of the noise reduction process. To evaluate the system, robot-based acceleration experiments integrated with programming exercises were conducted in our classroom. Through hands-on data collection and analysis, students developed a more concrete understanding of the fundamental laws of motion. The results indicated improvements in both the clarity and reproducibility of measurement data, along with positive effects on students' conceptual comprehension and perceived learning experience. In future work, the system's applicability will be extended to a broader age range, and its educational effectiveness will be systematically evaluated.

Keywords: Robot educational resources, Sensor data analysis, Measurement data accuracy, High school education, Physics education, Sensor noise, Noise filtering in robots, Kalman filter

1. Introduction

This Full Paper focuses on the theme of the relationship between displacement and acceleration. An instructional support system was developed to facilitate student engagement by minimizing extraneous cognitive load caused by measurement noise.

1.1. Background

Experiential learning through robot operation has been shown to be highly effective, particularly for beginner students [1]. In recent years, microcontroller- and robot-based experiments have been increasingly adopted in education [2]. Robotic teaching tools connect programming with real-world behavior via sensors and actuators, enabling students to intuitively understand and immediately test concepts across multiple disciplines. This cross-curricular approach aligns well with STEAM education, which promotes integrated learning in fields such as physics, mathematics, and computer science [3]. However, sensor noise often causes unstable measurement data in robotics experiments. For novice learners, identifying and resolving such noise is difficult and can hinder their understanding of the primary educational content. Based on Sweller's theory of cognitive load [4], [5], sensor noise is classified as an extrinsic cognitive load. As the extrinsic load increases, it becomes difficult for the learner to concentrate on the essential learning content of the experiment. For these reasons, it is necessary to make the novice learner unaware of the noise problem, even when measuring sensors using actual robot equipment.

1.2. Research objective

A system was developed to support high school physics education by reducing sensor noise in robotics experiments through unobtrusive filter processing. By minimizing extrinsic cognitive load, the system allows students to focus on core learning objectives without being distracted by data instability. The system was applied to the topic of displacement and acceleration, and students conducted constant acceleration experiments using mobile robots. Although the measurement data were pre-processed with a noise-reduction filter, students were unaware of this intervention. Comprehension and satisfaction were evaluated through post-class questionnaires to assess the system's educational effectiveness.

2. Methodology

2.1. Kalman filter

The Kalman filter is an algorithm that models a dynamic system using an “equation of state” and an “output equation” to integrate predictions with observed values, resulting in an optimal estimate [6]. The state equation predicts changes in the system’s state, while the output equation uses observed values to correct these predictions. This correction process balances the predicted and observed values to minimize uncertainty and provide accurate estimates. The filter operates by first predicting the system’s state at the next time step and then adjusting the prediction based on observed data. This revised estimate serves as the basis for subsequent predictions, which are continuously refined in real-time [7]. One key feature of the Kalman filter is its ability to weight predictions and observations according to their reliability, allowing for accurate estimations even when the system model is imperfect or the observed data are noisy.

2.2. Experimental vehicle “Orbit”

“Orbit” used in this experiment is a prototype robot we have been developing for educational purposes. The image and circuit diagrams are shown in Figures 1 and 2.

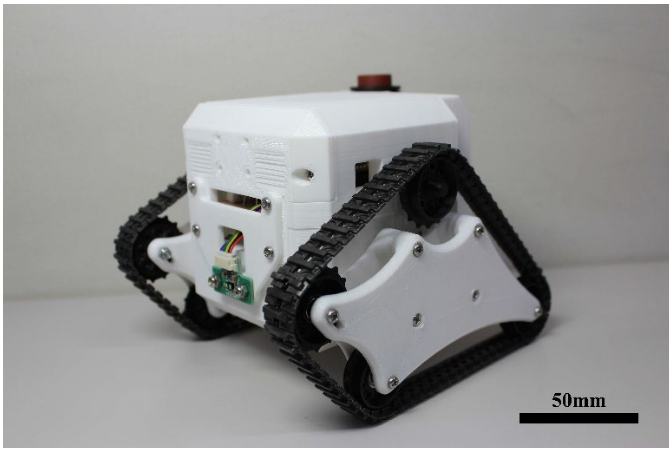

Figure 1 Orbit.

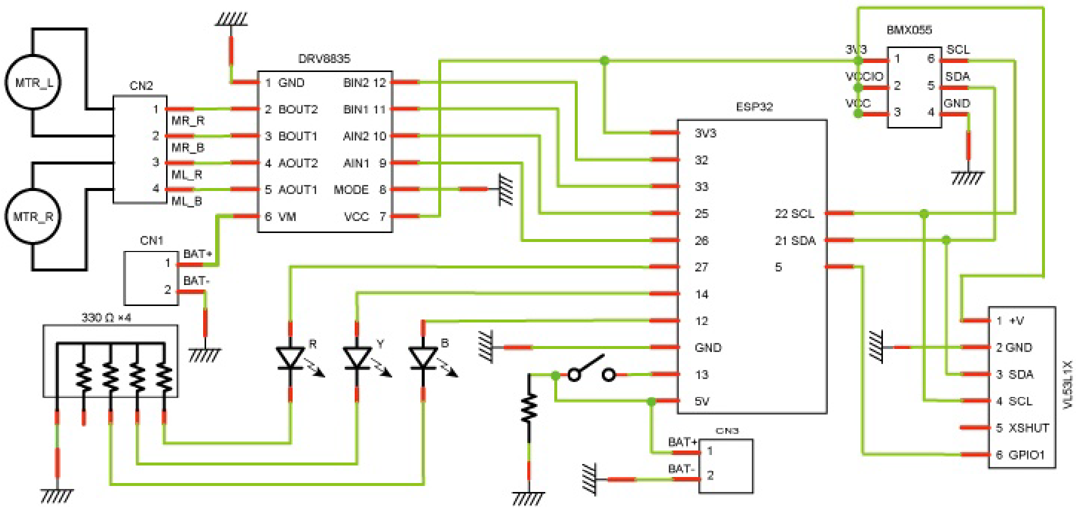

Figure 2 Circuit schematics of Orbit.

2.3. Class overview

In the implemented lesson, a measurement and analysis activity was conducted using an Orbit device subjected to uniformly accelerated linear motion toward a wall positioned in the direction of travel. Distance and acceleration data were acquired through onboard distance and acceleration sensors, respectively. The structure of the class proceeded as follows.

(1) An overview of the class activities was provided.

(2) Students assembled and wired Orbit devices.

(3) A programming session was conducted, during which students practiced code development and verified functionality using pre-distributed templates.

(4) Students were instructed to independently develop a program that controlled Orbit to perform motion with varying velocity, during which position and acceleration data were collected in real time.

(5) Two types of measurement experiments were carried out by students.

(6) A data analysis session was conducted, in which students interpreted and discussed the data they had collected. The discussion focused on the calculation of velocity and the degree to which the obtained graphs aligned with predictions. Additionally, students compared the average acceleration calculated from distance sensor data with the instantaneous acceleration recorded by the acceleration sensor.
(7) A questionnaire was administered to gather student feedback on the class.

In this class, students were organized into groups of two to three, with each group supported by a university student acting as a mentor. In addition, a facilitator and general support staff were assigned to oversee the overall progression of the class. The class adopts an integrated format that combines lectures and laboratory sessions [8].

For the preliminary programming activity, students used a template program created with PictoBlox, a block-based educational programming application designed for beginners. PictoBlox enables visual construction of programs, utilizing predefined blocks that encapsulate code internally, allowing intuitive operation. Subsequently, for programming tasks related to the experiment, Arduino IDE was used to implement and execute the required code.

In this class, regardless of prior programming experience, students were guided to develop logical thinking skills to derive correct solutions. To achieve this, instead of using blocks, paper was provided with the processing steps written out. Groups were tasked with organizing these steps in the form of a flowchart, based on the experimental procedure and the corresponding behaviors of Orbit. This exercise allowed students to rearrange steps as a simulation of flowchart construction. Building a program from a flowchart requires prior knowledge of programming, and writing out the entire code would be difficult to manage in terms of class progress. Therefore, a pre-made library was created. By using this library, two experimental programs, initially consisting of 297 and 289 lines of code, were reduced to just 11 lines each. While explaining the relationship between the block processing steps and the library, students were asked to reference the library and write the code required to execute the experiment. This allowed them to complete the programming task in a short amount of time while still engaging in the process of pseudo-programming. This structured approach facilitated step-by-step learning throughout the exercise.

The approach proposed in this study involves integrating a program within the library that applies a Kalman filter to essential blocks, such as “Start” and “Execute.” This method allows for the presentation of noise-reduced data without students being aware of the filter’s application.

2.4. Determining the conditions for the measurement experiment

To determine the course length for the Orbit, a performance evaluation of the distance sensor was conducted. A sufficiently large floor area was prepared, and Orbit, a chair serving as a wall, and a tape measure were set up. The position of the chair was set as the reference point at 0 millimeters, and distance data were collected from Orbit at intervals of 100, 200, 300, and so on, up to 2200 millimeters, with 1024 measurements taken at each position. Black paper was placed on the chair because the datasheet for the distance sensor indicated that a lower infrared reflectivity from the paper would be more suitable for short-range measurements. The data obtained are summarized in Table 1. A tolerance of 5 percent was applied in this evaluation. Based on the results, the starting and stopping positions were set to 1400 and 500 millimeters for Experiment 1, and to 2100 and 200 millimeters for Experiment 2.

Table 1 Measurement data.

Position (mm)	Measurement data (mm)			
	Minimum	Maximum	Mean	Standard deviation
100	77	102	89.5	5.3
200	186	199	192.4	2.2
300	280	297	287.7	2.4
400	376	394	385.0	2.6
500	478	496	485.5	2.4
600	571	584	577.8	2.4
700	669	682	675.7	2.2
800	775	790	783.1	2.6
900	871	886	878.8	2.7
1000	973	989	981.7	2.8
1100	1069	1090	1079.6	3.2
1200	1164	1187	1175.7	3.5
1300	1268	1288	1277.4	3.2
1400	1365	1391	1378.0	3.9
1500	1463	1490	1475.1	4.3
1600	1556	1585	1569.7	4.6
1700	1657	1685	1669.5	4.7
1800	1748	1783	1765.0	5.1
1900	1840	1875	1859.3	5.3
2000	1939	1979	1961.0	6.3
2100	2036	2072	2054.6	6.0
2200	2147	2193	2166.6	6.6

2.5. Development of the filter system

We created a program that controls Orbit in a straight line with constant acceleration, distance and acceleration data are measured applying a Kalman filter while Orbit is moving. Uniformly accelerated linear motion was achieved by varying the rotation speed of the motor using PWM control. A flowchart of the program is shown below as Figure 3.

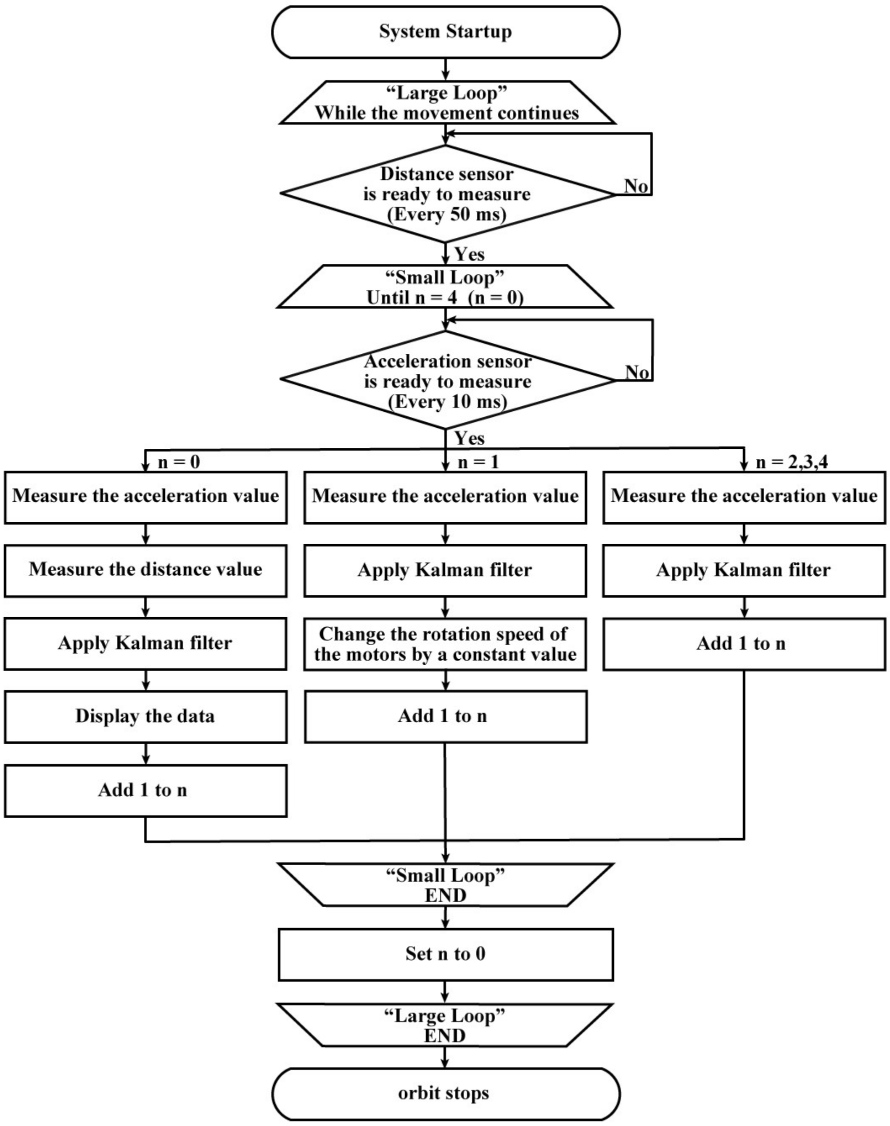

Figure 3 Flowchart.

3. Measurement experiment

Two classes were conducted incorporating the measurement experiments using the proposed filter processing system, and the system's effectiveness was evaluated based on the acquired data and student feedback. This course has been conducted twice so far. The first session took place on February 15th with a total of 27 students, consisting of 20 middle school students and 7 high school students. The second session was held on April 8th and 9th over two days at the affiliated high school of the university, with 7 high school students (Figure 4). This paper presents the evaluation of the second session.

3.1. Experimental method

In the class, two types of measurement experiments were conducted. The first involved uniformly accelerated linear motion that stopped when the maximum acceleration was reached. The second consisted of a sequence of motions: uniform acceleration, followed by constant velocity, and then uniform deceleration. The procedures for these experiments are described below. A schematic diagram of the experimental setup is provided in Figure 5.

(1) A chair covered with black paper was placed on a sufficiently large floor.

(2) The position of the chair was defined as 0 millimeters. A measuring tape was extended, and Orbit device was positioned at the 1400-millimeter point. The position was adjusted based on the reading from the distance sensor mounted on Orbit.

(3) Orbit was made to perform the action of Experiment 1, and data were collected.

(4) Orbit was placed at the 2100-millimeter mark using a measuring tape.

(5) Orbit was made to perform the action of Experiment 2, and data were collected.

(6) For each experiment, graphs with time on the horizontal axis and distance and acceleration on the vertical axis were generated from the acceleration-sensor data.

(7) For each experiment, , graphs with time on the horizontal axis and velocity on the vertical axis were generated from the distance-sensor data.

Figure 4 Class instruction.

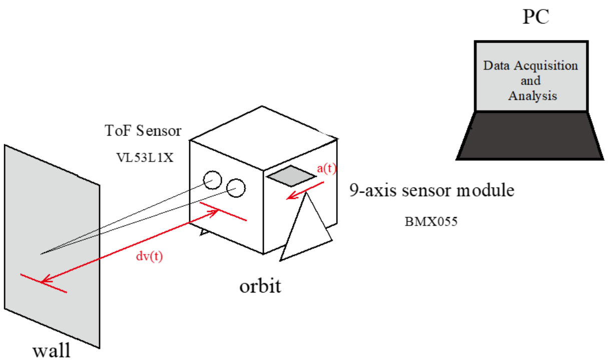

Figure 5 Schematic diagram of the experiment.

3.2. Experimental results

Graphs generated from the data obtained in Experiments 1 and 2 are presented below (Figure 6). These include distance-time graphs with time (s) on the horizontal axis and distance (mm) on the vertical axis, acceleration-time graphs with acceleration (mm/s²) on the vertical axis, and velocity-time graphs calculated from the acquired distance data. To support the discussion on the effectiveness of the filter processing system, each graph includes both the filtered and unfiltered data.

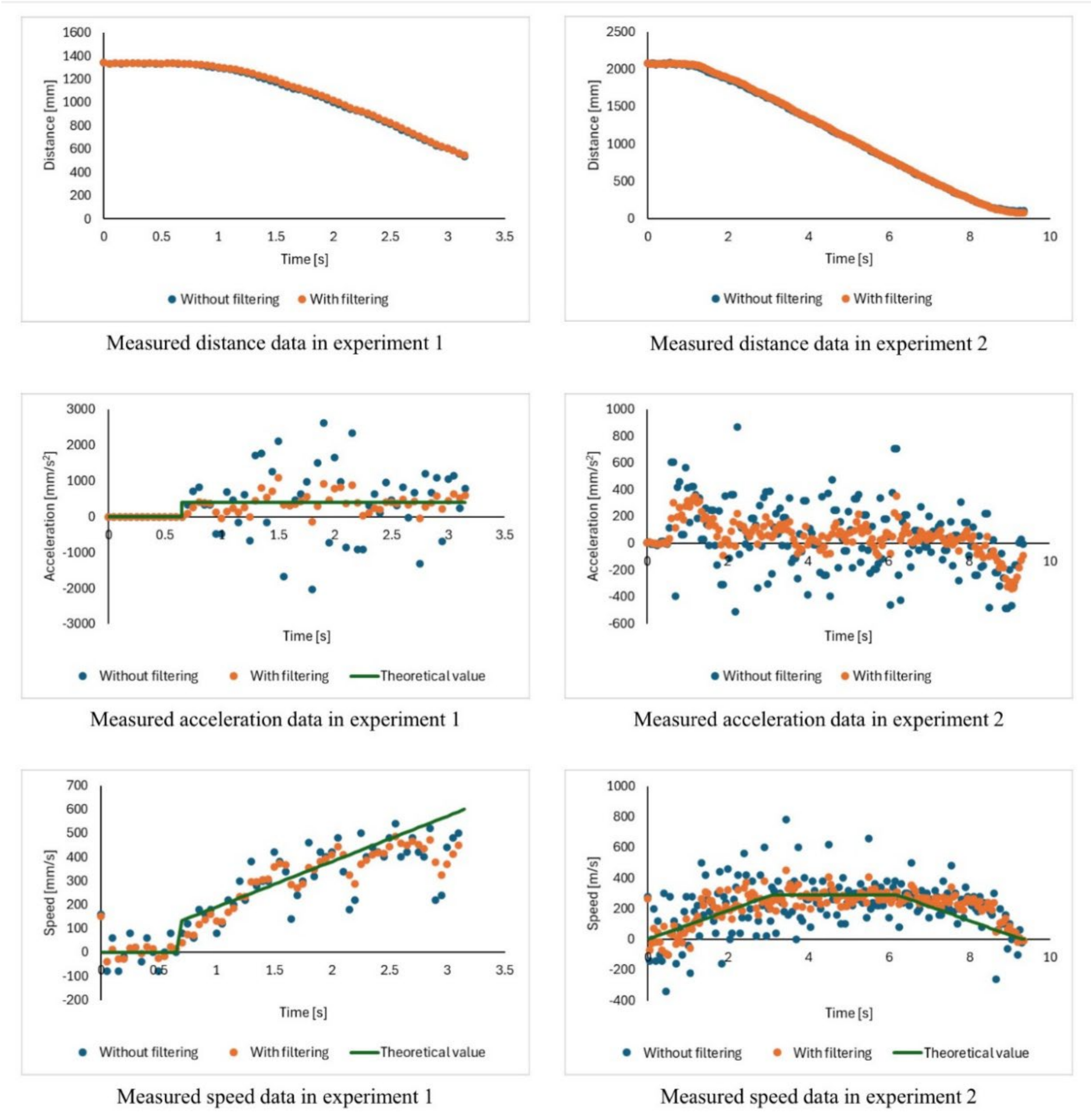

Figure 6 Effect of the Kalman filter on measured data.

3.3. Questionnaire results

To assess students' characteristics, learning outcomes, level of understanding, and overall satisfaction with the class, a questionnaire was administered at the end of the second session. The results of six selected items from the survey are presented below (Figure 7).

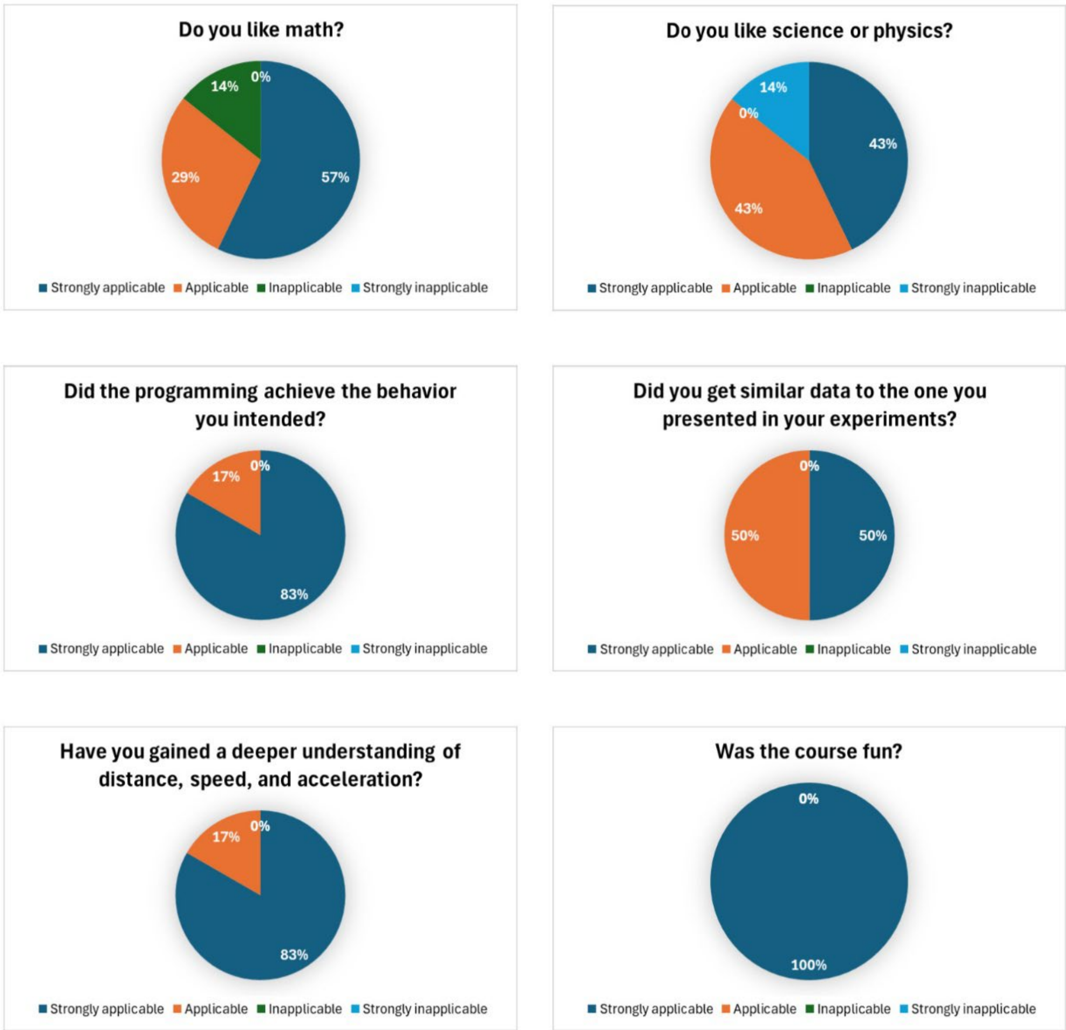

Figure 7 Survey results of the class (n = 6).

3.4. Discussion

First, the measurement data were analyzed. From the distance-time and acceleration-time graphs, it was observed that acceleration data were more susceptible to noise than distance data in both experiments. In all graphs from both experiments, Orbit remained stationary for a certain period before beginning to move. This behavior is attributed to a delay between program execution and the motor output reaching the threshold required for movement. In Experiment 2, the graph shape did not match the expected theoretical curve. This discrepancy is presumed to result from the program increasing motor output at fixed intervals without accounting for inertial or frictional forces. In the velocity graph of Experiment 1, significant fluctuations were observed, likely due to mechanical imprecision of the crawler system. A comparison of the graphs before and after applying the Kalman filter shows a substantial reduction in noise, resulting in curves that more closely resemble the theoretical model. In particular, the filtered velocity data exhibited a notable improvement in clarity, allowing the general shape of the graph to be discerned even from plotted measurement points. Based on the above findings, the effectiveness of the proposed filter processing system was confirmed. However, to obtain sensor data that more closely align with theoretical expectations, the control program must be improved by accounting for inertial force in order to achieve more accurate uniformly accelerated linear motion of Orbit.

Next, the results of the questionnaire are examined. Although the class included students who were not confident in mathematics or physics, the responses indicated a high level of achievement and understanding, along with an even higher level of overall satisfaction.

3.5. Future work

As this was the first implementation of the class, the number of participants was insufficient for a statistical analysis of the questionnaire results. To address this, regular future sessions are planned to increase the sample size. One such session is scheduled for August 30, 2025, with approximately 20 participants ranging from fifth-grade elementary to third-year junior high school students. In addition to the questionnaire, a brief test will be introduced to quantitatively assess student proficiency. Continued periodic implementation of the class is also under consideration. Following the second session class, feedback was received from a teacher at the hosting school, noting that “experiments involving not only constant acceleration but also variable acceleration have educational values, particularly because they are currently not included in existing curriculum-based classroom activities.” In light of this, future curriculum development will place greater emphasis on designing activities that address motion with changing acceleration.

4. Conclusion

This study proposed an instructional system aimed at enhancing students’ conceptual understanding of the relationship between displacement and acceleration by reducing extraneous cognitive load caused by measurement noise. The system incorporates a filtering mechanism within the data acquisition process, allowing students to analyze experimental results without being affected by signal irregularities, and without explicit awareness of the data having been filtered. The system was implemented in two classroom settings, where motion experiments and subsequent data analysis were conducted under controlled instructional conditions. Based on the results of post-class questionnaire responses, the instructional approach was found to be effective in promoting student engagement and comprehension. Ongoing efforts will focus on extending the applicability of the system to a wider range of age groups. Regular implementation is planned in order to increase the sample size and to conduct a more comprehensive evaluation of the system’s educational efficacy.

References

[1] J. Dewey, *Democracy and Education*. New York, NY, USA: Macmillan, 1916.

[2] Í. M. de Lima, E. V. de Souza, and F. D. V. de Araújo, “The use of Arduino as a methodological tool for teaching physics in high school,” *arXiv preprint arXiv:2001.08658*, 2020.

[3] National Academy of Engineering and National Research Council, *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research*. Washington, DC, USA: The National Academies Press, Mar. 2014.

[4] J. Sweller, “Cognitive load during problem solving: Effects on learning,” *Cognitive Science*, vol. 12, no. 2, pp. 257–285, 1988.

[5] J. Sweller, P. Ayres, and S. Kalyuga, “Cognitive architecture and instructional design,” *Educational Psychology Review*, vol. 10, no. 3, pp. 251–296, 1998.

[6] R. E. Kalman, “A new approach to linear filtering and prediction problems,” *J. Basic Eng.*, vol. 82, no. 1, pp. 35–45, 1960.

[7] H. Setiawan, A. Ma'arif, N. F. Ardhi, A. Nurhasanah, and H. Akmal, “Distance estimation on ultrasonic sensor using Kalman filter,” *Buletin Ilmiah Sarjana Teknik Elektro*, vol. 5, no. 2, pp. 129–136, 2020.

[8] J. Merricks, K. E. Cox, A. M. Moser, and S. A. Robertson, “Research and teaching: Integrating lecture and laboratory in health sciences courses improves student satisfaction and performance,” *J. Coll. Sci. Teach.*, vol. 49, no. 6, pp. 16–23, 2020.