Review Report for

Cobble motion characterisation with smart sensors through laboratory experiments for ground-based landslide monitoring

Alessandro Sgarabotto*, Irene Manzella, Kyle Roskilly, Miles J. Clark, Georgie L. Bennett, Chunbo Luo, Aldina M. A. Franco

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Table of Contents:

Round 1 Review

Comments by reviewer 1 (anonymous)

Completed: 2024-11-23 09:23 PM
Recommendation: Minor revisions

Reviewer Comments

For author and editor

It seems to me that the experience gained when carrying out these experiments and measurements is worth publishing.
There are same sentences that are not clear to me, such as when it is said that "gravity is compensated by adding gravity to obtain linear accelerations from the accelerometers" (line 210).
Please discuss the limitations inherent in using a camera in the field to locate smart cobbles that are embedded in a landslide (line 218).
Why is that the representation of raw data is called "high level" in line 355?
In figures 6 and 7, the use of boxplots is confusing. The white ones are undetectable because too short. I would use data points with different colors and error bars.
Mention in line 416 that the Kalman filter is detailed in the supplementary material appendix.
I strongly suggest to improve the quality of the prose since it does not always flow well.
The list of references is unfocused and too large.

Comments by reviewer 2 (Viviana Lourdes Gonzalez Blazek)

Completed: 2024-12-15 02:27 PM
Recommendation: Accept

Reviewer Comments

For author and editor

The paper presents an interesting and innovative approach to landslide monitoring using smart sensors embedded in boulders, which is relevant due to the increasing impact of climate change and urbanization on the frequency and intensity of these phenomena.
The title, "Cobble motion characterisation with smart sensors through laboratory experiments for ground-based landslide monitoring", is clear, precise and adequately reflects the content of the paper. The abstract provides a comprehensive overview of the study, addressing the objectives, methodology and key results.
The motivation for the research is well stated, highlighting the need for more accessible and reliable methods for landslide monitoring. The central hypothesis, that smart sensors can characterize boulder motions and transmit relevant data for early warning systems, is clearly stated and demonstrated throughout the paper.
The paper describes a robust and replicable methodology including the experimental design (wireless transmission tests using LoRaWAN and experiments on the movement of boulders on an inclined plane), and the description of the tools (the use of 9-axis MEMS sensors, high-resolution cameras, and data fusion techniques, including the Kalman filter, are detailed). The information provided is sufficient to replicate the experiments, especially with the cited supplementary material.
The figures and tables are well numbered and relevant, facilitating the understanding of the findings.
The bibliographic references are correctly cited and cover recent and relevant literature.
As for the results, the data show how the sensors can differentiate between motion modes (rolling and sliding) and quantify the magnitude of the motion in terms of kinetic energy. It incorporates as an innovation the use of LoRaWAN for data transmission through sandy media. This is novel and presents promising results, although with limitations in the sensitivity of the RSSI to sand coverage.
The conclusions are aligned with the objectives of the study and supported by the experimental results. It is recognized that smart sensors embedded in boulders can be effective for landslide monitoring and generating valuable data for prediction models.
The text is well organized, clear and easy to follow. No numerical errors were found, and the language used is technical and appropriate for the audience.
The article constitutes a valuable contribution and represents a significant advance in landslide monitoring. It is recommended for publication.
As an additional suggestion for future research work, I think it would be very interesting to expand the discussion on applicability in complex field conditions, such as irregular topographies and explore improvements in the stability of the sensor inside the boulder to minimize possible deviations in the measurement.

Comments by reviewer 3 (anonymous)

Completed: 2025-01-08 03:50 PM
Recommendation: Minor revisions

Reviewer Comments

For author and editor

General comment:

This manuscript introduces the characterization of cobble motion using low-cost sensors and data fusion for ground-based landslide monitoring. From the sensor perspective, the article's main contribution is to process raw sensor data from acceleration and position using the well-known Kalman filter. Also, the device is equipped with a LoRaWAN transmission for data streaming during experiments. The manuscript has an adequate structure and is mostly clear. The authors must address the following comments to improve the paper’s readability.

Comment 1:

I recommend summarizing the sensors’ parametric in a table including the most relevant features, sensitivity, resolution, power, etc..

Comment 2:

There is no mention of the computing facilities used for sensor calibration and data fusion. Was it implemented on an embedded processor or a general-purpose one? More technical details on it are missing.

Comment 3:

Under what assumptions did you derive the state-space model used by the Kalman filter? A simple but concrete derivation from the underlying physics is missing. Also, the proof of observability for the model is not included, such that you can guarantee the system is observable to estimate the internal states-

Recommendation by Associate Editor 2 (anonymous)

Completed: 2024-12-30 02:59 PM
Recommendation: Minor revisions
Reviewer Comments

For author and editor

The manuscript is mainly experimental, testing different sensors on concrete cobbles to analyze its movement when moving downslope. They test several slope angles and analyze when and how the cobble rolls and/or slides in the slope, its velocity, acceleration, changes in magnetic field, and other.

The manuscript is well written with a detailed methodological description, something to be expected in a experimental work. It is relevant for the journal and after minor revisions, it could be publishable.

Besides the comments from the other reviewers, some other things are not very clear. For example, which is the role of the sandy layer within different slope angles. In section 3.1. they point that some signals are sensitive to sand layer depths (by changing the rolling and sliding pattern), but the is no further mention of the sandy layer throughout the rest of the manuscript. Or maybe I missed something. It is not clear if all the experiments were performed with any layer of sand, which would emulate a real case scenario more accurately. Maybe add a paragraph to state this more clearly within the methodology section to justify your choice and a short paragraph in the discussions while analyzing the results.

Also the English needs to be checked:

L5 (check grammar); 239-241 (check grammar); 269 (sand medium?); 284 (respect?); 375-376 (...was not in a perfectly fixed position...); 479-480 (add prepositions); 489-490 (the sentence is confusing).

Supplementary material

(Frosio et al 2008)

'the angular velocity is expected to be null.'

gyroscope

'The offsets are measuerd by recording...'

'...due to the presence of...'

If the above observations, along with the observations done by the other two reviewers, are addressed, the manuscript could be ready for publishing.

Authors' responses to review comments

2025-02-13

RESPONSE TO THE COMMENTS

Please note that in this rebuttal, Reviewers' comments are denoted in black, our detailed response is in **blue**. Lines number refers to the manuscript with tracked changes.

EDITOR'S COMMENTS

Dear Authors

Thank you for submitting your manuscript entitled "Cobble motion characterisation with smart sensors through laboratory experiments for ground-based landslide monitoring" (42) to Geomorphica. I have now received three reviews and an Associate Editor assessment (included at the bottom and/or attached to this email). I have looked at the paper, the reviews and the Associate Editor recommendation myself.

On this basis, I would like you to undertake a **minor revision** of your manuscript. As this is a minor revision decision, we will assess the revised version internally and are unlikely to need to consult more widely before a final decision is made.

In order to facilitate timely publication of manuscripts submitted to Geomorphica, your revised manuscript should be uploaded as soon as you have made your revisions. We allow a **maximum of one month** for manuscripts which have been given a decision of minor revision - please submit your revision by **10 February 2025**. If it is not possible for you to submit your revision by the due date, please contact us for an extension by replying to this email.

Before submitting your revisions, please prepare the following documents:

1. A Response to Reviewers giving a point-by-point response to the reviewers' and Editors' concerns. In order to facilitate the processing of the revised manuscript, please be as specific as possible in your response. Should you disagree with the reviewers' comments, please provide explanations.
2. A "tracked" manuscript (word document or pdf), highlighting all the changes made in the document. Please try to address all the concerns raised by the reviewers and Editors within the manuscript.
   ***PLEASE NOTE: please check that all track changes files/response to reviewer files are also anonymized. This includes ensuring that the author of any editable documents is 'anonymous'.
3. A "clean" version of your revised manuscript where the changes are not marked.

As this is a minor revision decision, we suggest that you upload your text document (in Word or LaTeX format) and your figures (in eps, pdf, jpeg or tiff formats) as individual files. It is important that you follow the author guidelines (https://journals.psu.edu/geomorphica/authorguidelines) in doing this so that the figures are published at sufficient quality.

To submit your revised manuscript:

1. Log in by clicking on the link: https://journals.psu.edu/geomorphica/authorDashboard/submission/42
2. Files can be uploaded in the revisions section. Follow the instructions of the "Upload Review File" and add the appropriate new files (tracked manuscript, response to reviewers) and updated files (revised manuscript, possibly revised title page and figures)
3. Complete the process.

Once again, thank you for submitting your manuscript to Geomorphica and we look forward to receiving your revision.

Best wishes,

Alice Lefebvre

Editor-in-Chief, Geomorphica

Reply. We have complied with all recommendations for changes suggested by the AE and by the Reviewers. All changes are documented in detail below. We deem the updated version of the manuscript has been improved and want to thank you for the quality of the editorial work. In the point-to-point response, we refer to the line number of the manuscript file with track changes.

ASSOCIATE EDITOR'S COMMENTS

The manuscript is mainly experimental, testing different sensors on concrete cobbles to analyze its movement when moving downslope. They test several slope angles and analyze when and how the cobble rolls and/or slides in the slope, its velocity, acceleration, changes in magnetic field, and other. The manuscript is well written with a detailed methodological description, something to be expected in a experimental work. It is relevant for the journal and after minor revisions, it could be publishable. Besides the comments from the reviewers, some things are not very clear. For example, which is the role of the sandy layer within different slope angles. In section 3.1. they point that some signals are sensitive to sand layer depths (by changing the rolling and sliding pattern), but the is no further mention of the sandy layer throughout the rest of the manuscript. Or maybe I missed something. It is not clear if all the experiments were performed with any layer of sand, which would emulate a real case scenario more accurately. Maybe add a paragraph to state this more clearly within the methodology section to justify your choice and a short paragraph in the discussions while analyzing the results.

Reply. The experiments were designed to collect sensor data for different motion magnitude and mode of movement for cobble travelling down the incline. The motion magnitude was increased by changing the slope of the incline. Conversely, to collect data for mode of motion different from rolling, the cobble was embedded in a thin layer of sand reducing the friction on the table and favouring the establishment of a sliding motion for slope angles of 25°, 30°, 35°, 40° (tests G2, H2, I2, J2). For slope angles larger than 40°, sliding motion was not ensured and thus it was possible to carry out only rolling-type trials. We noticed that there was an oversight in Table 1 since it reported sliding experiments at slope angles even though those trials had not been carried out. We corrected Table 1 (please see below the corrected version of Table 1). Moreover, in the methodology section, we clarified the reason why we carried out sliding experiments only on four slopes (lines 270-276): "For slopes of 25˚ to 40˚, the same experiments were also carried out embedding the cobble in a thin sand layer (~0.5 cm) to reduce the friction on the table and favour sliding motion. [...]. For slope angles larger than 40°, sliding motion was not ensured and thus it was possible to carry out only rolling-type trials."

Table 1. Experimental campaigns. In the first experimental campaign, the sensor secured in a plastic box and buried under a sand layer of different thickness was moved so that Received Signal Strength Indicator (RSSI) and the Signal-to-Noise ratio (SNR) were sent to LORIOT network service through LoRaWAN. In the second experimental campaign, cobble motion down an inclined plane was tested for different mode of movements and slope inclination. Three repeats for each test were conducted (tick symbol stands for 3 repeats).

First experimental campaign: Testing LoRaWAN under sand layers			
Experiment series	**Sand layer thickness (mm)**		
A	0		
B	5		
C	8		
D	10		
E	15		
Second experimental campaign: Testing MEMS for cobble motion			
Experiment series	**Slope inclination**	**Rolling experiments**	**Sliding experiments**
F1	18°	✓	
G1	25°	✓	
G2	25°		✓
H1	30°	✓	
H2	30°		✓
I1	35°	✓	
I2	35°		✓
J1	40°	✓	
J2	40°		✓
K1	45°	✓	
L1	50°	✓	
M1	55°	✓	

Also the English needs to be checked:
L5 (check grammar); 239-241 (check grammar); 269 (sand medium?); 284 (respect?); 375-376 (...was not in a perfectly fixed position...); 479-480 (add prepositions); 489-490 (the sentence is confusing).

Supplementary material
(Frosio et al 2008)
'the angular velocity is expected to be **null.**'
gyroscope
'The offsets are measured by **recording**...'
'...due to **the** presence of...'
Reply. We have corrected all the misprints and grammar mistakes highlighted by Associate Editor in the Manuscript and Supplementary Material.
If the above observations, along with the observations done by the reviewers, are addressed, the manuscript could be ready for publishing.
Recommendation: Minor revisions

We thank Associate Editor for reading through the manuscript providing constructive criticism and suggestion to improve the manuscript.

REVIEWER#1'S COMMENTS
It seems to me that the experience gained when carrying out these experiments and measurements is worth publishing.
We thank the Reviewer for their evaluation.
1) There are same sentences that are not clear to me, such as when it is said that "gravity is compensated by adding gravity to obtain linear accelerations from the accelerometers" (line 210).
Reply. We corrected the oversight (lines 228-230): "Fourth, linear accelerations were inferred from the accelerometers through gravity compensation". Moreover, the manuscript has been proofread.
2) Please discuss the limitations inherent in using a camera in the field to locate smart cobbles that are embedded in a landslide (line 218).
Reply. The sensor is also equipped with a GPS sensor that was deactivated to carry out the laboratory trials. In field applications, the information on the position can be obtained by the GPS. We added this information in the Discussion section (lines 517-519): "The sensor used in this study is also equipped with a GPS that, although remained deactivated in the laboratory trials, can record the location of the smart boulder outdoors pending a satellite coverage (Miromico manual, 2020a, b)."
3) Why is that the representation of raw data is called "high level" in line 355?
Reply. For sake of clarity, we replaced "High level representation of raw data" with "Lumped representation of motion from raw data" (lines 379 and 430).
4) In figures 6 and 7, the use of boxplots is confusing. The white ones are undetectable because too short. I would use data points with different colours and error bars.
Reply. Figures 6 and 7 were changed replacing boxplots with error bars and using different colours to increase the readability.

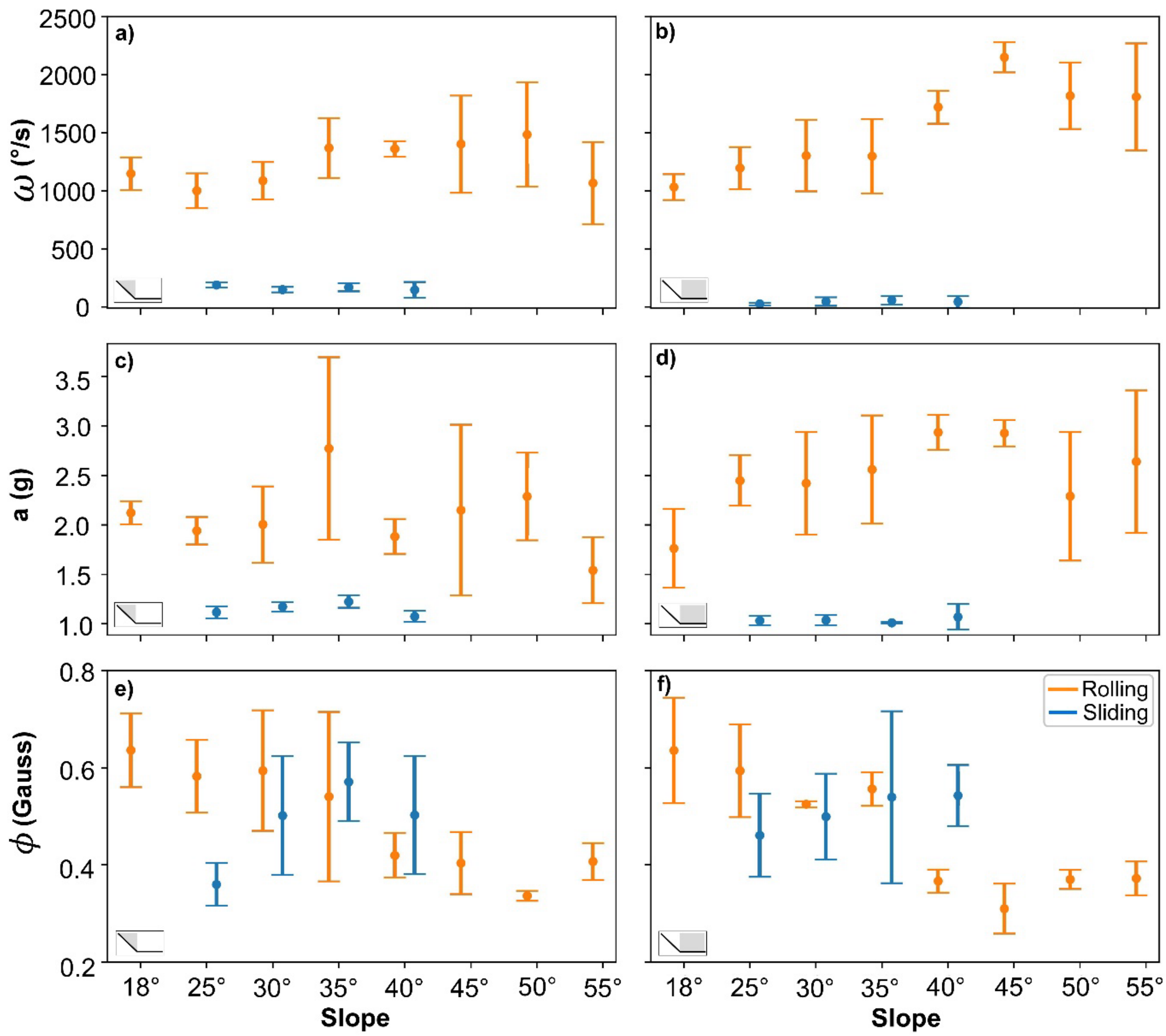

Figure 6. Lumped representation of cobble motion for rolling and sliding experiments using raw data. (a, c, and e) Error bars for motion on the inclined plane. (b, d, and f) Error bars for the motion on the horizontal plane. The mean magnitude of (a and b) angular velocity, (b and c) acceleration, and (e and f) magnetic field. Amber error bars refer to experiments with a sliding cobble, whereas blue error bars are tests with a rolling cobble.

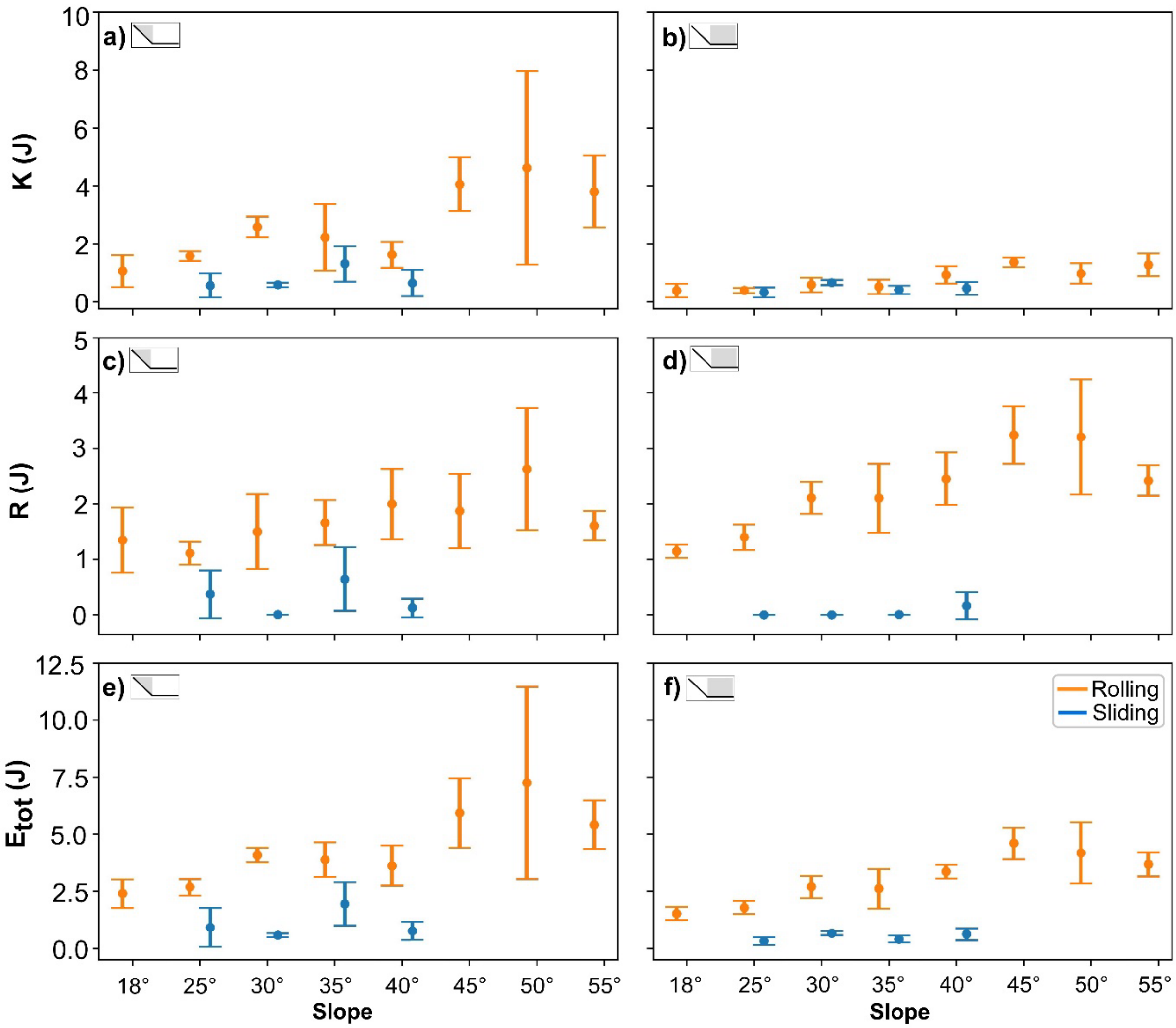

Figure 7. Error bars of (a, b) the mean translational kinetic energy K, (c, d) rotational kinetic energy R and (e, f) total kinetic energy E_{tot} in rolling and sliding experiments. (a, c, and e) Motion on the inclined plane. (b, d, and f) Motion on the horizontal plane. Amber error bars refer to experiments with a sliding cobble, whereas blue error bars describe tests with a rolling cobble (m =0.7 kg; R = 0.05 m; I = 1.68 kg·m^2).

4) Mention in line 416 that the Kalman filter is detailed in the supplementary material appendix.
Reply. Thank you for raising this point. We added this detail in the sentence (444-447): "The linear velocity is computed through the Kalman filter fed by the camera-based positions and sensor-based linear accelerations (See the Supplementary Material for further details), whereas the angular velocity is inferred from the orientation angles (Section 2.3, Figure 3)."
5) I strongly suggest improving the quality of the prose since it does not always flow well.
Reply. A thorough proofreading was conducted to correct the misprints following Reviewers' suggestion and improve the narrative.

6) The list of references is unfocused and too large.
Reply. The list of references was reduced by deleting 18 references and it was improved by keeping the focus on landslide monitoring. Some references were deleted because introducing the topic from a too generic perspective (e.g., Kumar et al., 2019). Some references were deleted because old-dated (e.g., Saito, 1969, Voight, 1988).
Recommendation: Minor revisions

We thank the Reviewer for reading through the manuscript providing constructive criticism and suggestion to improve the manuscript.

REVIEWER#2'S COMMENTS
The paper presents an interesting and innovative approach to landslide monitoring using smart sensors embedded in boulders, which is relevant due to the increasing impact of climate change and urbanization on the frequency and intensity of these phenomena.

The title, "Cobble motion characterisation with smart sensors through laboratory experiments for ground-based landslide monitoring", is clear, precise and adequately reflects the content of the paper. The abstract provides a comprehensive overview of the study, addressing the objectives, methodology and key results.

The motivation for the research is well stated, highlighting the need for more accessible and reliable methods for landslide monitoring. The central hypothesis, that smart sensors can characterize boulder motions and transmit relevant data for early warning systems, is clearly stated and demonstrated throughout the paper.

The paper describes a robust and replicable methodology including the experimental design (wireless transmission tests using LoRaWAN and experiments on the movement of boulders on an inclined plane), and the description of the tools (the use of 9-axis MEMS sensors, high-resolution cameras, and data fusion techniques, including the Kalman filter, are detailed). The information provided is sufficient to replicate the experiments, especially with the cited supplementary material.

The figures and tables are well numbered and relevant, facilitating the understanding of the findings. The bibliographic references are correctly cited and cover recent and relevant literature.

As for the results, the data show how the sensors can differentiate between motion modes (rolling and sliding) and quantify the magnitude of the motion in terms of kinetic energy. It incorporates as an innovation the use of LoRaWAN for data transmission through sandy media. This is novel and presents promising results, although with limitations in the sensitivity of the RSSI to sand coverage.

The conclusions are aligned with the objectives of the study and supported by the experimental results. It is recognized that smart sensors embedded in boulders can be effective for landslide monitoring and generating valuable data for prediction models.

The text is well organized, clear and easy to follow. No numerical errors were found, and the language used is technical and appropriate for the audience.

The article constitutes a valuable contribution and represents a significant advance in landslide monitoring. It is recommended for publication.

As an additional suggestion for future research work, I think it would be very interesting to expand the discussion on applicability in complex field conditions, such as irregular topographies and explore improvements in the stability of the sensor inside the boulder to minimize possible deviations in the measurement.
Reply. We have changed some parts in the Discussion and in the Conclusion to highlight the potential of the study in view of MEMS application in field trials:
(lines 498-546): "Our laboratory experiments have given us insights into the possibilities and challenges of smart boulders for landslide monitoring and early warning field applications. Despite some limitations in the camera and sensor settings dictated by laboratory and design constraints, the protocol and methods developed here are able to provide a lumped representation of the motion magnitude, determine the mode of movement of the cobble and test its signal transmission. Firstly, it seems possible from our experiments with a sand-filled bucket of different depths (section 3.1) to obtain a signal from partially buried sensors, though in a complex field setting this will inevitably also depend on other factors such as geology, topography, atmospheric conditions etc. Preliminary data from field experiments conducted in parallel to our laboratory experiments also suggest that this is the case, with signal obtained even from partially buried sensors (Roskilly et al. 2023; Newby et al., 2024). Laboratory experiments on the style of cobble movement show the potential of IMU sensors for monitoring landslides by detecting the style of movement e.g. by rolling or sliding, and magnitude of movement. Thus, by analysing the activity of boulders distributed on a landslide, it should be possible to analyse landslide movements in time and space. Boulder activity would possibly help to map the boundaries of zones where displacements occur (e.g., Dini et al., 2021) and monitor movement of the underlying landslide. The sensor used in this study is also equipped with a GPS that, although remained deactivated in the laboratory trials, can record the location of the smart boulder outdoors given satellite coverage (Miromico manual, 2020a, b).

Whilst there are benefits of a technology that can move with the landslide over more traditional techniques that may be disrupted by landslide movement, boulders may not remain fully embedded in the body of the landslide for the entire duration of the motion and thus may not always represent underlying landslide movement. The sensor recordings from the field thus need to be carefully analysed to determine whether boulder motion is representative of deeper-seated landslide movement or more surficial movements in flows or rock falls. Moreover, LoRaWAN technology has to provide low-latency data transmission with respect to the timescale of the events being monitored. Thus, the time lag between sensor recording and data retrieval should be carefully studied in field sites. To allow timely data transmission for early-warning system applications, it would be advisable to rapidly characterise the motion of the boulder by computing a high-level metric on-board the sensor (such as the total kinetic energy proposed in this study) and then send this via LoRaWAN with highest priority. "
(lines 569-573): "In view of possible application for monitoring and early warning of landslides, in this study we tested the ability of novel smart sensors to track and characterize cobble motion and send data via wireless network in laboratory experiments."
Recommendation: Minor revisions

We thank the Reviewer for reading through the manuscript providing constructive criticism and suggestion to improve the manuscript.

REVIEWER#3'S COMMENTS

General comment:
This manuscript introduces the characterization of cobble motion using low-cost sensors and data fusion for ground-based landslide monitoring. From the sensor perspective, the article's main contribution is to process raw sensor data from acceleration and position using the well-known Kalman filter. Also, the device is equipped with a LoRaWAN transmission for data streaming during experiments. The manuscript has an adequate structure and is mostly clear. The authors must address the following comments to improve the paper's readability.

1) Comment 1:
I recommend summarizing the sensors' parametric in a table including the most relevant features, sensitivity, resolution, power, etc..

Reply. Thank you for your suggestion. We added a table to summarise the technical parameters regarding the sensors deployed in the laboratory trials. Please find below the new table added (Lines 207-208).

Table 1. Main sensor parametric features (Miromico manual, 2020a, b).

MEMS	
Power supply	3.6 V battery
3-axis sensor (ST LIS2DH)	2 Hz
Parameter	
Accelerometers	±2g
Acquisition frequency	2 Hz
Acceleration threshold to wake 9-axis sensor	390 mg
9-axis sensor (ST LSM9DS1)	
Parameter	
Accelerometers	±16 g
Gyroscopes	±2000 °/s
Magnetometers	±16 Gauss
Acquisition frequency (Accelerometers, Gyroscopes)	14.9 Hz or 59.5 Hz
Acquisition frequency (Magnetometers)	5 Hz
LoRaWAN	
Parameter	
Received Signal Strength Indicator (RSSI)	from -120 dBm to -30 dBm
Signal-to-Noise ratio (SNR)	from -20 dB to 10 dB

2) Comment 2:

There is no mention of the computing facilities used for sensor calibration and data fusion. Was it implemented on an embedded processor or a general-purpose one? More technical details on it are missing.

Reply. Thank you for raising this question. The data fusion and sensor calibration were not implemented in an embedded processor but developed within the study. By collecting different samples from every sensor, we calibrated accelerometers following the optimisation method described in Frosio et al. (2009), gyroscopes subtracting offset values for each axis (Glueck et al., 2019) and magnetometers following the optimisation method (Dewhirst et al., 2016). The data fusion approach to couple camera-based position and sensor-based acceleration was carried out using a linear Kalman filter.

In the Supplementary material we added the plot of raw recordings used for the calibration (Figures S1, S2, and S3). Please find the figures below. Regarding the data fusion details, we addressed the point in the reply to comment 3.

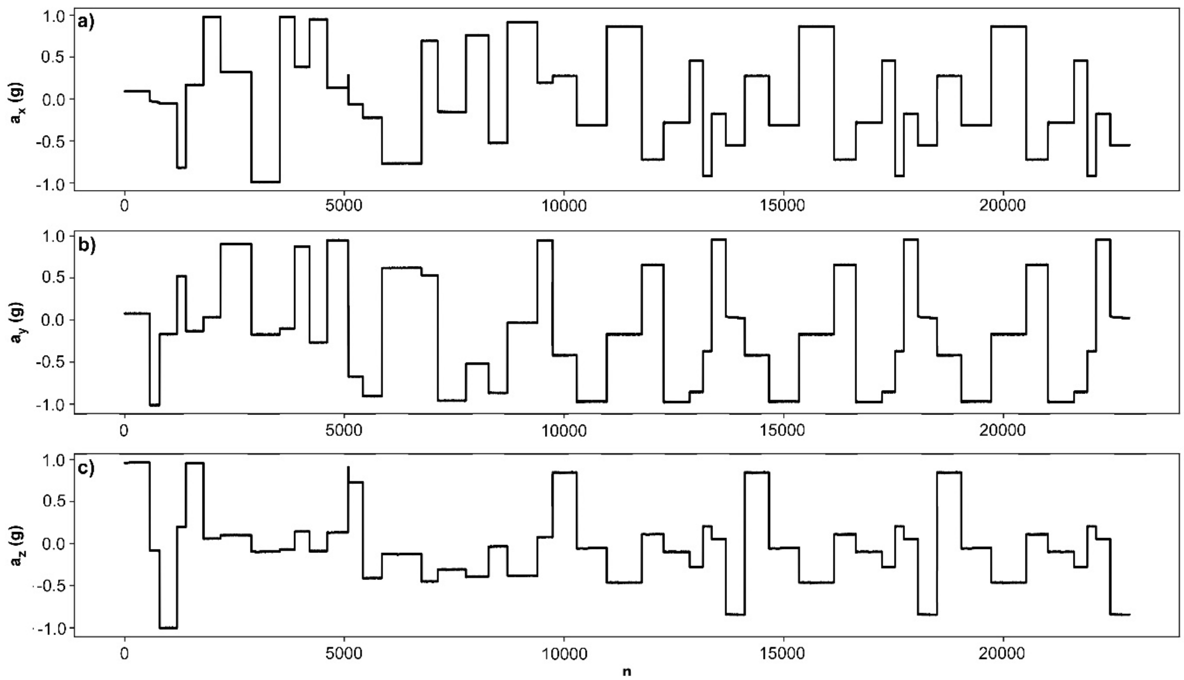

Figure S1. Raw acceleration recordings in static positions used for accelerometer calibration.

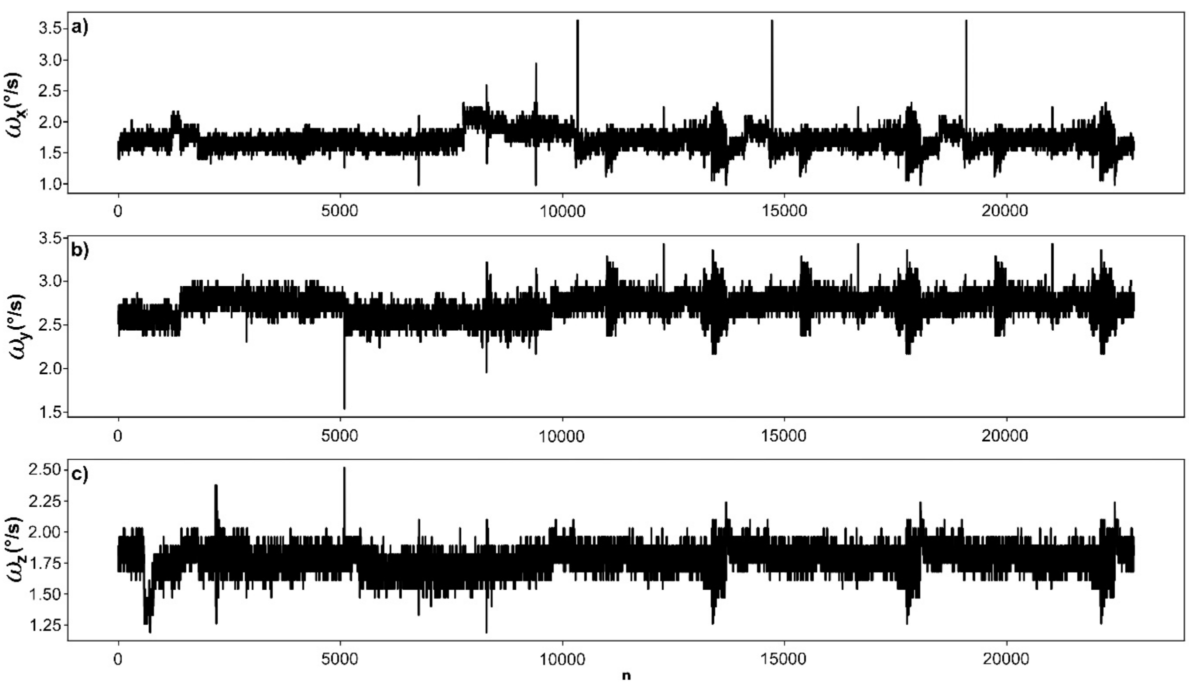

Figure S2. Raw angular velocity recordings in static positions used for gyroscope calibration.

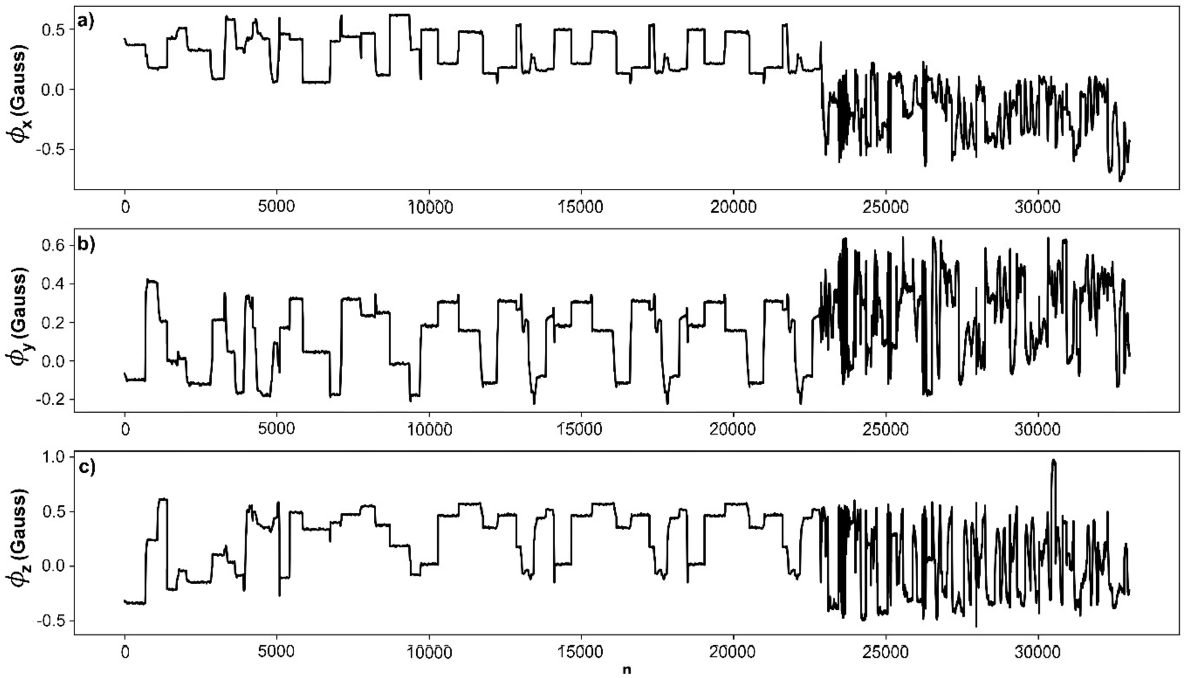

Figure S3. Raw magnetic field recordings used for magnetometer calibration.

3) Comment 3:
Under what assumptions did you derive the state-space model used by the Kalman filter? A simple but concrete derivation from the underlying physics is missing. Also, the proof of observability for the model is not included, such that you can guarantee the system is observable to estimate the internal states-

Reply. In the Supplementary material, we have introduced the assumptions of the methodology proposed and shown a comparison between the trajectory inferred from the present methodology and some frameworks based on motion equation.

"

<u>Limitation</u>

The sensor-based motion reconstruction via Kalman filter is based on some assumptions. First, the cobble is assumed to keep a point of contact with the experimental table (Figure 1). Second, the sensor embedded in the cobble is assumed to remain fixed during cobble motion. The present methodology shows some limitations. When the table inclination is small (<45˚), the point of contact is ensured. However, for higher inclinations, the cobble starts losing contact with the board and thus the vertical elevation in camera-derived positions, that is computed assuming a point of contact with the board, becomes more approximated. Furthermore, the cotton pad buffer in the sensor enclosure does not ensure a fixed sensor installation position within the cobble increasing the degree of approximation of the motion reconstruction via Kalman filter. This notwithstanding, the variation of the kinetic energy reasonably explains the magnitude of the movement for changes in slope and mode of movement (Figure 7). The camera and sensor fusion are thus able to provide a lumped representation of the motion magnitude and determine the mode of movement."

"

Comparison with analytical frameworks

We compared the results of the data fusion algorithm with some simple conceptual analytical models, namely the rigid motion over a tilted plane and pendulum oscillations around a frictionless pivot (Figure S4).

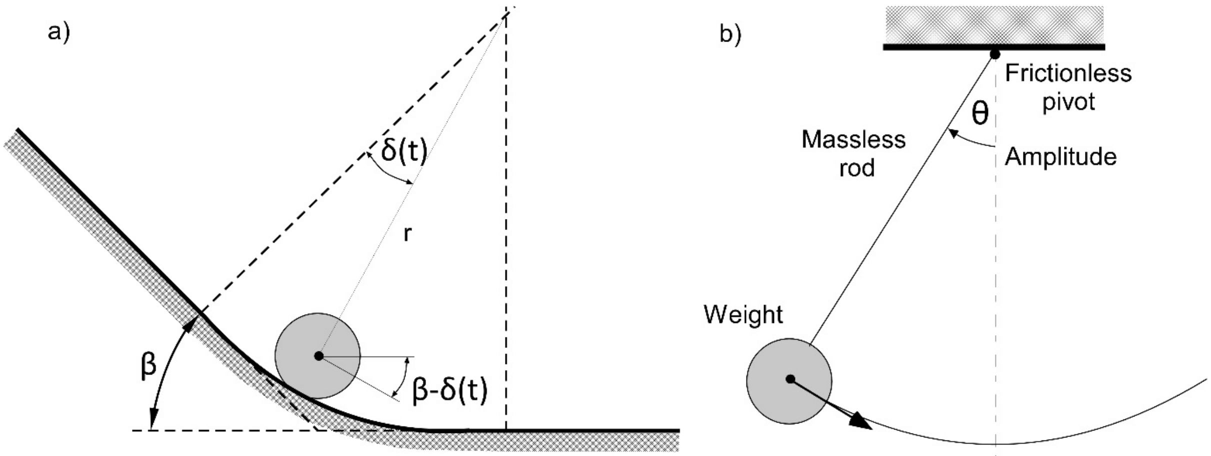

Figure S4. Simple conceptual frameworks to assess the robustness of the sensors data. (a) Rigid body motion over a tilt plane where β is the tilt plane slope, Φ the dynamic friction angle, and r is the radius of curvature. (b) Pendulum oscillations around a frictionless pivot where L is the length of massless string and θ is the angle the weight of the pendulum forms with the vertical.

Taking for example the experiments with an incline of 30°, the trajectories of cobbles travelling down the slope are represented in Figure 1. For the rolling experiments, the cobble average trajectory is smooth showing a larger variability on the slope (Figure S5a). Then, when the cobble is on the horizontal board, the trajectory has a low variation from the average showing some wiggles due to the uneven cobble surface that makes the rolling motion irregular (Figure S5). Conversely, in sliding experiments, the cobble trajectory is smoother along the whole path (Figure S5b). Similarly to the rolling case, the variability of the cobble path is smaller on the horizontal board and is slightly larger on the slope. In both examples, the standard motion equation describes a path that matches the experimental trajectories with an acceptable degree of approximation.

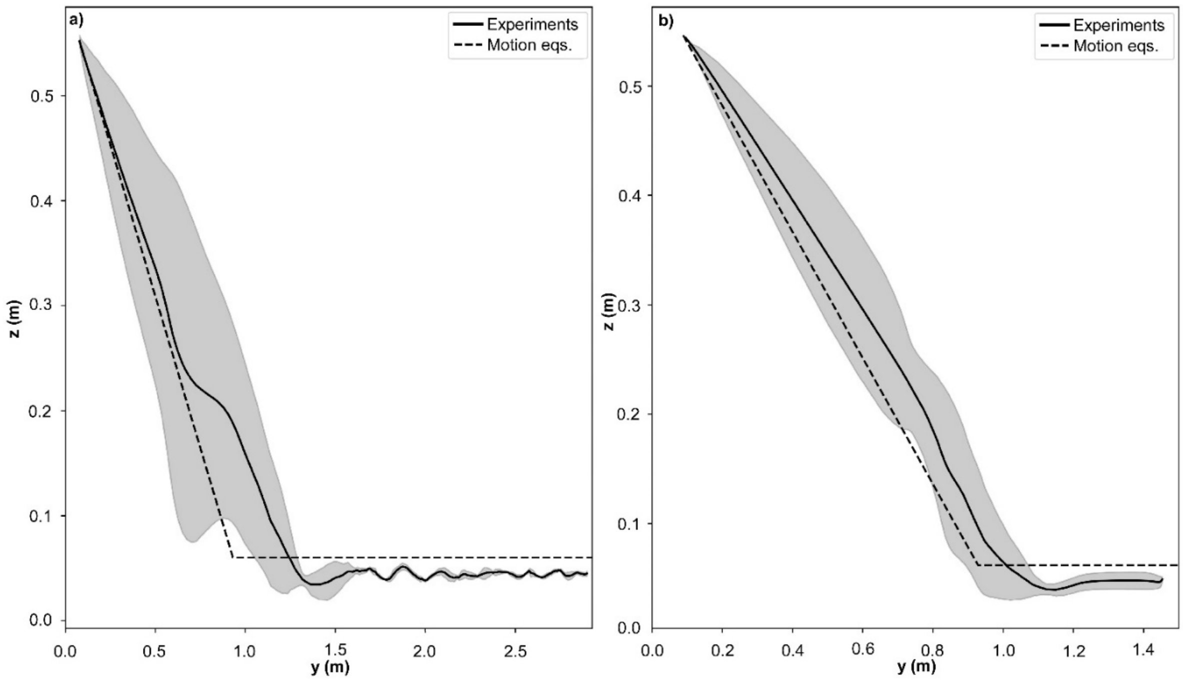

Figure S5. Comparison between the experiments and the standard motion equation describing the trajectories of the cobble for a slope at 30˚ in the vertical plane z-y. (a) Rolling experiments where the motion equation response is obtained for a friction angle Φ = 7.5˚. (b) Sliding experiments where motion equation response is obtained for a friction angle Φ = 2.5˚. Solid lines represent the average behaviour during the experiments at the same slope, whereas the grey areas show the standard deviation of the variable considered.

The pendulum trajectory is represented in Figure S7a. Overall, the experimental trajectories match the motion equation results reasonably well when the pendulum length and the initial angle are set at 2.05 m and 19˚, respectively. The experimental pitch angle is compared to the motion equation angular displacement in Figure S7b. The motion equation prediction overestimates the average pitch angle, and the experimental oscillations do not show a periodicity similar to the pendulum conceptual model. However, the experimental pitch angle ranges between -17.5˚ and 13.5˚ which is in good agreement with the motion equation angular displacement ranging between -19˚ and 19˚. “

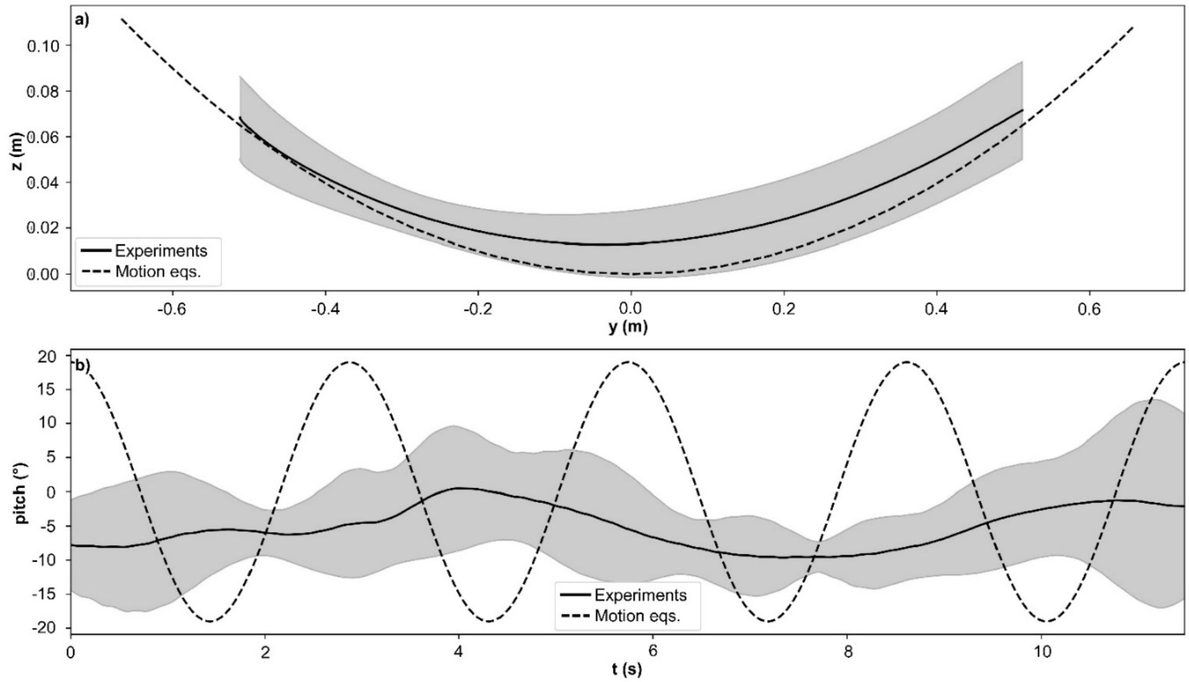

Figure S7. Comparison between the experiments and standard motion equation. (a) Trajectories in the vertical plane z-y. (b) The angle the weight of the pendulum forms to the vertical. Motion equation response is obtained for pendulum length L = 2.05 m and initial oscillation angle θ_0= 19˚.

Recommendation: Minor revisions

We thank the Reviewer for reading through the manuscript providing constructive criticism and suggestion to improve the manuscript.

Round 2 Review

Recommendation by Associate Editor 2 (anonymous)

CCompleted: 2025-02-28 06:36 PM
Recommendation: Accept