nature portfolio

Peer Review File

Kirigami-inspired parachutes with programmable reconfiguration

Corresponding Author: Professor David Melancon

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)
I have read the manuscript with great interest, and the authors have explored a beautiful and elegant idea. Indeed, they apply the traditional Japanese art of Kirigami to fabricate parachute-like structures. These structures are simple disks made porous by the application of cuts. When subjected to flow, the loading of the structure induces large deformations that help the deployment of this new type of “parachute” and, ultimately, allow its slow descent in the air. Like I said, I find the idea beautiful. The paper is also beautifully illustrated. My biggest concern regarding publication in Nature is the following:
The concept of using cuts to alter the shape of an object has now been largely studied in the soft matter community. As noted by the authors, this idea has also been explored in the presence of flow. As such, there is little fundamental novelty in fluid-structure interaction here. I appreciate and am impressed by the quality of the numerical results, but one could perceive these improvements as iterative — thus not warranting publication in Nature.

Conversely, the work is the first to explore the flight of these structures (free flight, not in a wind tunnel). That is the part of the work which (1) is the novel and where the results are the most impressive (Fig 4) and (2) the most likely to generate excitement in the soft matter community and the broader audience. Thus, the authors should rethink the way the manuscript is written, putting more emphasis on flight capabilities and studying some essential aspects of this process. The results in Fig1b-d are very different from a simple free fall, yet the authors mainly focus on U_\infty (admittedly the most important parameter to characterize flight, but not the only one). More knowledge is needed here. Does the parachute tumble? If yes, what is the frequency? Where do they land compared to the vertical to the origin of flight? What happens if there is some side wind? Or if the payload is distributed differently than attached in the middle?

Can these parachutes achieve something exciting that a regular parachute could not do? I would suggest, for example, stacking many disks (10-100) and dropping them at once from a drone or something of the like. These disks could be identical or even better different (2 populations), e.g., allowing them to sort themselves during the fall. The manuscript could also benefit from an explicit discussion of the limitations of this approach. Could we go bigger? How would these contraptions compare with regular parachutes?

In conclusion, I find the idea beautiful but would like to see the concept pushed further before I can recommend publication.

(Remarks on code availability)

Referee #2

(Remarks to the Author)
Key results:
This work studies how kirigami structures change shape amidst fluid flow. It uses kirigami cuts to manufacture parachutes.

The kirigami patterns can be laser cut into a disk which deploys into a parachute shape upon falling through air. The kirigami patterns are not new - there is no attempt to design them for this purpose, or indeed optimize them.

The paper has simulation, experimental, and analysis components which generally agree. The authors build a meter-scale kirigami parachute and find that it can help an object maintain a more vertical trajectory when drifting to the ground, and that it slows the fall down. The kirigami parachute is theoretically easier to manufacture than a conventional parachute because it uses lasercuts instead of seams and folds. However, it is almost certainly true that the cuts will grow and might fail catastrophically - so likely this can be used once - which is quite wasteful compared to parachutes: the large demo parachute in this paper still has pieces which must still be taped together, and this is not scalable. The kirigami parachutes slow the terminal velocity comparably to conventional parachutes in a low load-to-area ratio regime. It looks like conventional parachutes begin outperforming the kirigami parachutes at about 2.25lbs to m^2 weight to area ratio (10N/m^2).

Originality and Significance:
The topic and potential application of this work are interesting but not particularly surprising. Streamlining parachute manufacturing improves their potential for airdropping items to people. Additionally, fluid interaction behavior is a potentially interesting area of the kirigami materials field.

However, the potential noteworthiness of this paper comes from the kirigami parachute application, which is very limited in its applicability. Kirigami parachutes perform comparably to conventional parachutes only for small weight to area ratios, which is interesting but not remarkable. The demo parachute in this paper also still needs to be pieced together with seams, and is not yet easier to manufacture than a conventional parachute. The other findings in this paper are nice, but not significant relative to advances in kirigami technology, so the parachute demonstration falls a little flat.

Falling disks and wind tunnel experiments:
These experiments show that there is a regime of kirigami cut patterns in a disk which causes a large z-axis extension ("Mode K") and improved stability when the disk falls.

The authors should address more clearly why Design A and other patterns could lack a Mode K. There's a discussion on line 287 which says the extension limit of Design A's Mode C is given by r_0 - r_1, but why does Design A not have a Mode K at all, even at higher flow velocities? Visually, it seems the reason is geometric.

Minor notes:
Fig. 1b-d is a nice visualization of what the different trajectories look like.
In some locations 1e is said to display the standard deviation of displacement, while in other locations it says "Lateral displacement" (in-figure x-axis label on Fig. 1e, combined with the first sentence in the caption "Lateral displacement as a function…"). It's confusing, and it would be good to make it clear that the standard deviation is being plotted.
The "cylindrical mode C" the authors describe is not really a cylinder, as the ends wrapping around the cylinder never turn back inward.

Simulation framework:
The simulation results agree nicely with the experiments above.

Parachute demonstration:
The kirigami parachute slows the fall down to about 40% of free fall velocity (line 616, 673).

There are terminal velocity vs. W/A curves for winged seeds and for an ideal parachute. The colored points in Fig. 4a should be the kirigami parachutes, but what do the different colored markers mean?

What are the authors saying in line 586?

Suggested improvements

• Was the water bottle or camera damaged after landing with the kirigami parachute?
• In Fig. 4a, the kirigami parachute is comparable in slowing the fall to a conventional parachute in a certain regime (up to around 10^1 N/m^2). Is this a realistic regime for airdrops of helpful items? Where on this graph would the water bottle experiment fall (both predicted and experimental results)?
• The authors should provide more clarity on how accurately the theoretical transition model can predict whether a cut pattern deforms into mode C or K. In the current text, it seems like the simulations are only accurate when the deformation mode is already known.
• The authors claim the kirigami parachutes can offer stability "without consideration of the initial release orientation". Is this supported anywhere?

(Remarks on code availability)

Version 2:

Reviewer comments:

Referee #1

(Remarks to the Author)
This is the second time I am reviewing this manuscript, so I will focus on the differences to the first manuscript. I believe that the work is improved and I appreciate that the authors have carefully answered all my queries. Of course more work is always possible, but I see no reason to further delay publication and I am happy to recommend that the manuscript should be accepted in its present form. Here is why:

As previously stated, the design and the mechanics of kirigami has been the topic of several studies in the soft matter community in the last few years. This includes the interaction of kirigami structure with flows. Yet, this work is the first of its kind to explore the flight of kirigami structures. I think this is a beautiful idea, and the authors have developed a significant body of knowledge on this topic. The application of their work to practical settings is convincing. It is indeed easy enough to laser cut the patterns they report and use it in the field. These results, and their application will generate the type of excitement that one can expect from articles in a journal like Nature. As such, I reiterate my support towards publication.

(Remarks on code availability)

Referee #3

(Remarks to the Author)
The authors describe a novel parachute design, made by placing azimuthal cuts in a thin plastic sheet (fig 1). The effect of the cut pattern on aerodynamic behaviour is measured and simulated with a recently introduced toolkit (fig 2,3). Experimental results for two cut patterns are obtained and compared to air-dispersed seeds and ideal parachutes (fig4). A metre-scale sample is produced and used to safely deposit a water bottle from around 60m elevation (fig5).

The concept of shape-morphing kirigami and the study of its behaviour under flow is not new. However, this work provides an important advancement: it demonstrates how to translate previous theoretical work into a practical application. I believe that this is a necessary and broadly welcomed development in the field of architected structures. In addition, the experimental, theoretical, and numerical work are well carried out and reported.

That said, the manuscript would benefit from a sharper narrative and updated figures. The parachute application is central to the work's importance. The authors show that, at low load-to-area ratios, kirigami parachutes can match the typical terminal velocity of conventional ones, and improve control over lateral drift. However, this result is not clearly stated in either the abstract, the introduction, fig. 4, or the discussion around fig 5, and is only partially addressed in the conclusions. I would recommend that the authors update the manuscript to help understand readers what is being achieved here (matching terminal velocity and improved lateral precision).

Significant notes:
- fig 2c—e, fig3a, fig3c: are error bars included here and simply not visible?
- line 303: please refer to the SI equation or section where the added stiffness is defined.
- line 310: is the choice of 28 for the stiffness criterion an ad hoc one to separate the populations in fig.3b? Please add an explanation in the SI.
- line 614: "stability": does this refer to lateral displacement, vibration sensitivity, or something else?
- fig 4b: including the results of fig. S9 here would be very helpful to clarify the utility of a kirigami parachute.
- line 852: please provide a rough estimate for the observed lateral displacement of the parachute.

If the authors address these concerns, I can recommend publication in Nature.

Minor comments:
- line 14-15: ref. 19 looks at undesired motion of supersonic parachutes, which is not relevant here.
- line 25: "reduce the risk to human life" is not clearly motivated.
- line 20: "closed-loop" is confusing here, please add a citation or omit the term.
- line 48: ref. 39 refers to an APS meetings abstract, please reformat citation.
- Fig.1: panel b—d: adding a schematic at the top to illustrate the circular cutting patterns would be very helpful. Panel e: please add the complete lateral displacement data, or provide it in an SI figure.
- line 111: please define U_infty as the wind tunnel air flow speed here.
- line 177: r_1 should be r_i.
- line 303: please show the unity slope in fig. 3a.
- in fig.3b, is the added stiffness measured or calculated?
- if possible, add a legend instead of inserted labels in fig.4a.

Questions on SI:
- line 113-114: define exactly which deformation regime was used to fit the stiffness of the various samples. If possible, indicate this in fig. S4. Linear fit results can depend a lot on fitting regime, and it would be great to quantify this e.g. using error bars in fig. 3a.

- line 225: “alpha” is mentioned but not defined.
- line 312: C_2 is not defined and may be mixed up with C_1.

(Remarks on code availability)

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Kirigami-inspired parachutes with programmable reconfiguration

Manuscript number: 2024-07-13735A

Danick Lamoureux[a], Jérémi Fillion[a], Sophie Ramananarivo[b], Frédérick P. Gosselin[a], and David Melancon[a]

[a]Laboratory for Multi-Scale Mechanics (LM2), Department of Mechanical Engineering, Polytechnique Montreal, 2500 chemin de Polytechnique, Montreal (Quebec), H3T1J6, Canada; [b]LadHyX, CNRS, École Polytechnique, Institut Polytechnique de Paris, 91120, Palaiseau, France

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Remark on the review process

We would like to thank the editor and reviewers for their thorough evaluation of our manuscript. The initial submission was made to *Nature* in July 2024, and we received the first round of comments in early January 2025. In their feedback, the editor recommended further development of the application of kirigami-inspired parachutes and granted us 4 to 6 months to complete the revision. Before we received the reviewers' comments, the first author, Danick Lamoureux, completed his MSc in July 2025 and subsequently began a PhD at EPFL. Most of the additional experimental work was performed in the Winter 2025 semester by Jérémi Fillion, an undergraduate intern at Polytechnique Montreal, which we have added as a new co-author.

Response to the editor

Title – this should be no longer than 75 characters (including spaces), and should be focused firmly on the main result of broad interest (the parachute application).

We have modified the title as follows: *Kirigami-inspired parachutes with programmable reconfiguration*

Abstract/summary paragraph – this is of an appropriate length and style (indeed, it could be up to 50 words longer if that would help), but needs to cite references.

We are now citing references in the abstract.

Body text – at 3,800 words, this is much longer than we would normally allow (2,500-3,000 words is the target that you should aim for). You might consider adding a formal Methods section to the end of the paper and make use of our Extended Data format to help make the necessary reductions while leaving room for more experimental results (e.g. some of the simulation work could perhaps be relocated there, in addition to some of the current supplementary information?)

We have made substantial efforts to reduce the length of the text in our manuscript while adding new experimental data that focus on the parachute application. As per the editor's suggestion, we have added a formal *Methods* section in which we have included the details of our design, fabrication, simulation, and tests. In the revised version of our manuscript, we have highlighted in yellow the new text and left in ~~strikethrough~~ the text we have removed. For easier reading, we have also included a clean version of the revised manuscript with no highlights.

Response to reviewer #1

I have read the manuscript with great interest, and the authors have explored a beautiful and elegant idea. Indeed, they apply the traditional Japanese art of Kirigami to fabricate parachute-like structures. These structures are simple disks made porous by the application of cuts. When subjected to flow, the loading of the structure induces large deformations that help the deployment of this new type of "parachute" and, ultimately, allow its slow descent in the air. Like I said, I find the idea beautiful. The paper is also beautifully illustrated.

We are glad reviewer #1 found our research article beautiful and elegant. We have addressed their comments and revised our work accordingly. In particular, we have reshaped the structure of the main manuscript, added new figures, and performed new experiments to further emphasize the parachute application. We hope reviewer #1 will agree it is now suitable for publication in *Nature*.

Comment 1A

My biggest concern regarding publication in Nature is the following: The concept of using cuts to alter the shape of an object has now been largely studied in the soft matter community. As noted by the authors, this idea has also been explored in the presence of flow. As such, there is little fundamental novelty in fluid-structure interaction here. I appreciate and am impressed by the quality of the numerical results, but one could perceive these improvements as iterative — thus not warranting publication in Nature.

The reviewer is right that deploying shapes and objects via the kirigami art of paper cutting through mechanical (1, 2) or fluid-driven (3, 4) actuation has been studied in the soft matter community. The novelty of our work lies in applying the fluid-structure interaction of kirigami sheets to design and fabricate parachutes, a direction that, to our knowledge, has not been previously explored. To highlight this distinction, we have added the following text in the introduction of our manuscript:

> While leveraging kirigami principles to deploy shapes and objects under mechanical (7,42) and fluid (21,22) actuation has been studied, we apply these concepts to the design and deployment of kirigami-inspired parachutes, a direction that, to our knowledge, has not been previously explored."

In addition, we have performed additional experiments to strengthen the part of our manuscript describing the application to kirigami-inspired parachutes. See **Comments 1B**, **1D** and **1I**.

Comment 1B

Conversely, the work is the first to explore the flight of these structures (free flight, not in a wind tunnel). That is the part of the work which (1) is the novel and where the results are the most impressive (Fig 4) and (2) the most likely to generate excitement in the soft matter community and the broader audience. Thus, the authors should rethink the way the manuscript is written, putting more emphasis on flight capabilities and studying some essential aspects of this process.

We appreciate the reviewer's input and agree that the novelty is indeed the application of kirigami to design new kinds of parachutes. To further characterize the flight capabilities of our kirigami-inspired parachutes, we performed new drop testing on Designs A and B (deforming in a cylindrical mode $\mathcal{C}$ and Kirigami mode $\mathcal{K}$ under flow, respectively) to study their free fall kinematics. For these new tests, we manufactured the kirigami-inspired parachutes out of 0.311 mm thick shims with outer radius of $r_o = 215$ mm and inner radius of $r_i = 21$ mm. These dimensions allowed us to screw a bottle of water on the parachutes' center which was equipped with a 6-axis accelerometer (AX6 from Axivity) with its z-axis opposed to gravity. The total payload was 144 g, including the weight of the parachute itself. We launched each parachute three times indoors from a height of 14.9 m and recorded their lateral, $\ddot{x}$ and $\ddot{y}$, and vertical, $\ddot{z}$, accelerations at a sampling rate of 200 Hz. During the fall, we observed that Design B (deforming in mode $\mathcal{K}$) fell steadily, while Design A (deforming in mode $\mathcal{C}$) descended with a high tumbling amplitude resulting in an unsteady vertical acceleration. This can be observed in Fig. R1b, where we plot the vertical acceleration $\ddot{z}$ of Design A (solid blue curve) and B (solid green curve) as a function of time. By integrating the average of the vertical acceleration $\ddot{z}$, we obtained the vertical velocity $\dot{z}$ over time. The results, shown by the dashed lines in Fig. R1b, reveal that the terminal velocity is $U_\infty = 2.44\,\mathrm{m\,s^{-1}}$ for Design A and $U_\infty = 4.29\,\mathrm{m\,s^{-1}}$ for Design B. In comparison, the terminal velocity of free fall from a height of 14.9 m is $U_\infty = 17.09\,\mathrm{m\,s^{-1}}$. In addition to measuring acceleration of our parachutes during free fall, we characterized their lateral drift in an indoor flight situation with little to no cross-wind. The kirigami-inspired parachutes manufactured for these tests have a thickness of $t = 127\,\mu\mathrm{m}$ and an outer radius of $r_o = 100\,\mathrm{mm}$, with an inner hole of radius $r_i = 3\,\mathrm{mm}$ to attach the payload. The payload consists of a screw and a bolt with a mass of 12.6 g. We dropped multiple parachutes Designs A and B from a height of 16.6 m with different initial release angles: 0°, 45° and 90°. We then measured the distance between each parachutes' landing spot and a ground target representing their

initial release position. As mentioned above, we observed that Design A (deforming in mode $\mathcal{C}$), while slower, descended unsteadily. This lead to significant lateral drift for design A, landing at a completely random distance from the ground target as plotted in Fig. R1c (blue bars). On the other hand, we observed that Design B (deforming in mode $\mathcal{K}$) had high precision with consistently low lateral displacement, regardless of the initial release angle (see green bars in Fig. R1c). To take into account these new experimental results and put more emphasis on the novelty of the parachute application, we have made several changes to our manuscript. First, we split Fig. 4 of the original manuscript into two figures which are reproduced in Figs. R1 and R2 for completeness.

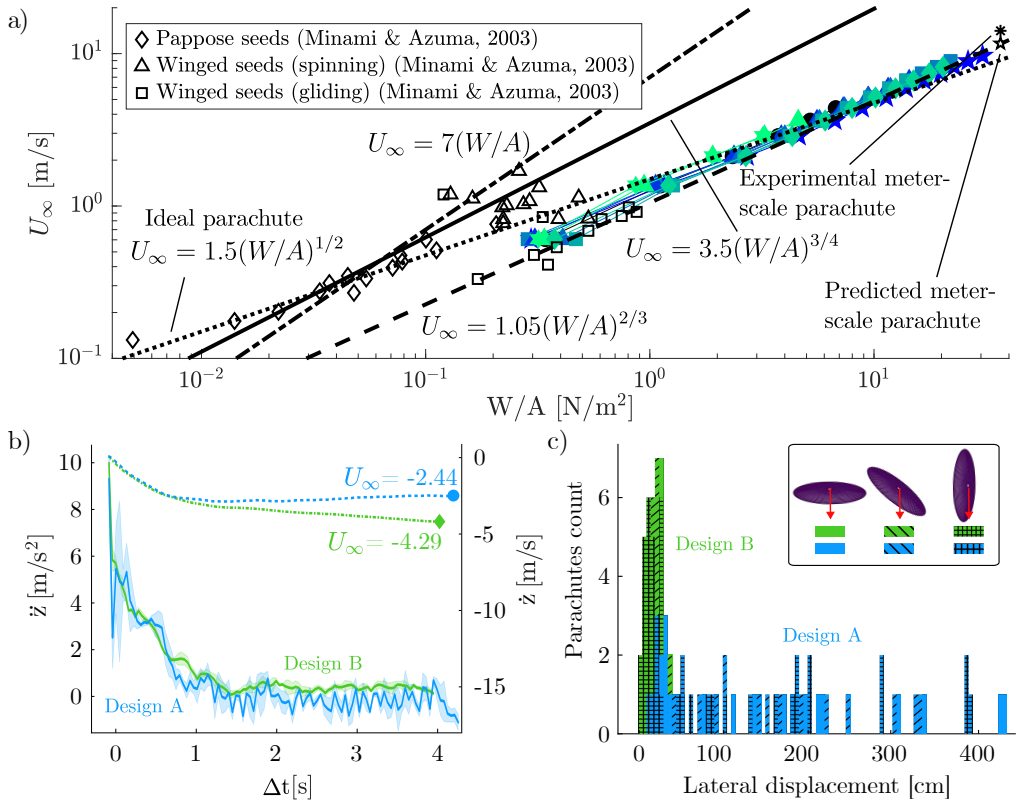


Fig. R1. Performance of kirigami-inspired parachutes. a) Terminal velocity U_∞ as a function of load per unit of area W/A for different species of wind-dispersal seeds (40) and our kigirami-inspired parachutes (colored markers, with the same colors that were used in Fig. 3a). The lines are trends and fits identified by Ref. (40), with the black dotted line the relationship of an ideal parachute. The black asterisk and star are the experimental and predicted terminal velocities of the meter-scale parachute discussed in this work. b) Vertical acceleration, $\ddot{z}$, and velocity, $\dot{z}$, of kirigami-inspired parachutes Designs A and B. The solid lines and shaded areas are the average and standard deviation of the vertical acceleration of three fall experiments measured with an accelerometer. The dashed lines are the vertical velocity obtained by integrating numerically the mean vertical acceleration of three fall experiments. c) Lateral displacement of kirigami-inspired parachutes Designs A and B across multiple drop tests. The solid bars represent parachutes launched at 0°, the hatched bars at 45°, and the crosshatched bars at 90°.

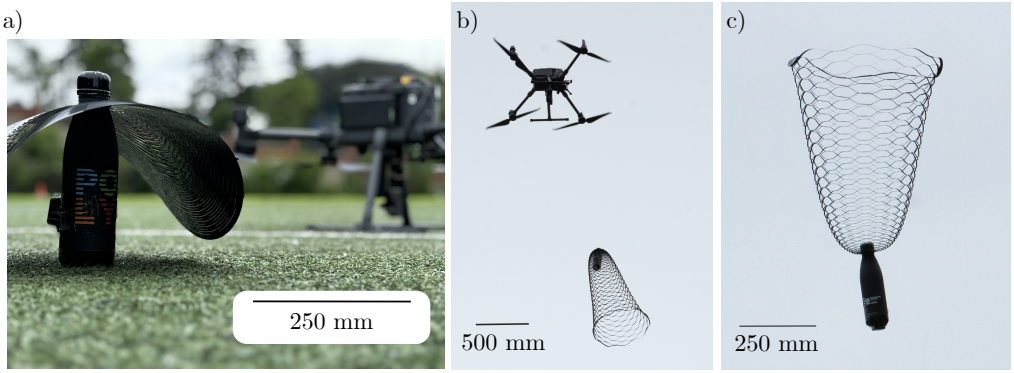


Fig. R2. Kirigami-inspired parachute in realistic conditions. a) Water bottle mounted on a kirigami-inspired parachute attached to a drone. b) Parachute elongating as the drone pulls it up to its dropping altitude of 60 meters. c) Snapshot of a kirigami-inspired parachute during free fall in realistic conditions.

Second, in the *Introduction* section, we have modified the text as follows:

> "Here, we focus on the closed-loop kirigami pattern (see Fig.1a) and, taking inspiration from wind-dispersal seeds (40) and deciduous tree leaves (41), we build kirigami-inspired parachutes that exploit their quasi-axisymmetric deformation under flow to program the aerodynamic stability of thin circular sheets in free fall. [...]"

> "Finally, we build kirigami-inspired parachutes and characterize their flight performance by dropping them indoors above a target and outdoors from a drone to deliver a bottle of water."

Third, in the *Results* section, we also explain the utility of the reconfiguration, $\mathcal{R}$ and elongation, δ, curves as it pertains to parachuting applications:

> "The reconfiguration curve shown here can be used as a tool to design the best free falling parachute for a given disk. To maximize drag and ensure free-fall stability in a deployed state, the Cauchy number should be minimized while respecting the constraint that $\bar{K} < 28$ through the use of an appropriate kirigami pattern."

> "We note that the elongation law can also be used to ensure parachute stability. Indeed, if the parachute does not extend enough during falling, then the aerodynamic moment generated might not be sufficient to ensure vertical falling, and could behave as a rigid falling disk, which is known to tumble (46)."

Fourth, we report the new experimental data of Fig. R1 in the *Results* section:

> "We first characterize the flight capability of kirigami-inspired parachutes based on Designs A and B (see *Methods* for details). We launch each parachute three times indoors from a height of 14.9 m and record their lateral, $\ddot{x}$ and $\ddot{y}$, and vertical, $\ddot{z}$, accelerations. Fig. R1b reports the vertical acceleration, $\ddot{z}$, as a function of time (lateral accelerations and tumbling frequencies are reported Fig. S8). We find that Design A (solid blue curve) deforming in mode $\mathcal{C}$ descends with an unsteady vertical acceleration. In comparison, the acceleration of Design B (solid green curve) deforming in mode $\mathcal{K}$ plateaus after 2 seconds of flight. By integrating the average of the vertical acceleration $\ddot{z}$, we can obtain the vertical velocity $\dot{z}$ over time (dashed lines in Fig. R1b). The results reveal that the terminal velocity is $U_\infty = 2.44\,\mathrm{m\,s^{-1}}$ for Design A and $U_\infty = 4.29\,\mathrm{m\,s^{-1}}$ for Design B. In comparison, the terminal velocity of free fall from a height of 14.9 m is $U_\infty = 17.09\,\mathrm{m\,s^{-1}}$.
>
> In addition to their deceleration during free fall, we characterize the lateral drift of Designs A and B in a flight situation. For this purpose, we drop multiple parachutes from a height of 16.6 m with three initial release angles: 0°, 45°, and 90°. We then measure the distance between each parachutes' landing spot and a ground target representing the initial release position. Fig. R1c reports the distribution of the lateral displacement during the drop tests for parachutes Design A (blue bars) and Design B (green bars) launched at 0° (solid bars), 45° (hatched bars), and 90° (crosshatched bars). Coherently to the acceleration results, we observe that Design A, while reaching a lower terminal velocity, shows a random distribution of lateral drift. This situation is similar to that of a conventional parachute, which also exhibits significant lateral drift during free fall (see Fig. S9). On the other hand, we observe that Design B consistently falls close to the target, regardless of the initial release angle. (see Fig. R1c). This highlights that kirigami-inspired parachutes deforming in mode $\mathcal{K}$ can quickly reach terminal velocity, provide increased stability, and drop near intended targets if used to deliver humanitarian aid."

Fifth, we describe the fabrication of the kirigami-inspired parachutes used in these new tests in the *Methods* section:

> "***Fabrication of kirigami-inspired parachutes***
> To record the lateral, $\ddot{x}$ and $\ddot{y}$, and vertical, $\ddot{z}$, accelerations of the kirigami-inspired parachutes in Fig. R1b), a 6-axis accelerometer (AX6 from Axivity) was mounted on the parachutes. For this purpose, larger parachutes inspired by the kirigami disks Designs A and B were lasercut in polyester plastic sheets (see section S2 (5) for more details on the manufacturing process). The parachutes have a thickness of $t = 311\,\mu\mathrm{m}$ and an outer radius of $r_o = 215\,\mathrm{mm}$, with an inner hole of radius $r_i = 21\,\mathrm{mm}$ to attach the payload. The payload consists of the accelerometer and a water bottle, totaling a mass of 0.144 kg. To make sure that the larger parachutes keep the same stiffness of the kirigami disks Designs A and B, we adjust their cutting parameters as described by $\{\Delta r_1, \Delta r_2, n, N_\theta, \Theta\} = \{10\,\mathrm{mm}, 6.13\,\mathrm{mm}, 1.0, 8, 0.3\}$ (Design A), and $\{10\,\mathrm{mm}, 6.13\,\mathrm{mm}, 1.0, 5, 0.3\}$ (Design B).
>
> The kirigami-inspired parachutes used to characterize the lateral drift of Designs A and B in Fig. R1c) have a thickness of $t = 127\,\mu\mathrm{m}$ and an outer radius of $r_o = 100\,\mathrm{mm}$, with an inner hole of radius $r_i = 3\,\mathrm{mm}$ to attach the payload. The payload consists of a screw and a bolt with a mass of 12.6 g. Their cutting parameters are described by $\{\Delta r_1, \Delta r_2, n, N_\theta, \Theta\} = \{3\,\mathrm{mm}, 2.85\,\mathrm{mm}, 1.0, 8, 0.3\}$ (Design A), and $\{3\,\mathrm{mm}, 2.85\,\mathrm{mm}, 1.0, 5, 0.3\}$ (Design B)."

Comment 1C

The results in Fig1b-d are very different from a simple free fall, yet the authors mainly focus on U_∞ (admittedly the most important parameter to characterize flight, but not the only one). More knowledge is needed here.

Figs. 1b-d of the main manuscript show snapshots of three kirigami disks during free fall from a height of about 1.75 m. This first set of experiments serves to highlight that some cut patterns are associated with smaller lateral drift as reported in Fig. 1e.

In turn, this motivates the study of the reconfiguration of our kirigami disks under flow of velocity U_∞ which unveils that disks deforming in mode $\mathcal{K}$ are associated with an aerodynamic moment M that is inversely proportional to the angle of attack α. This explains the small lateral drift seen in disks (Fig. 1) and parachutes (Figs. 4 and 5) deforming in mode $\mathcal{K}$. We agree with the reviewer that U_∞ is not the only variable needed to characterize flight. We refer to the answer of **Comment 1B** where we have presented other variables such as lateral and vertical accelerations as well as lateral displacement from a fall of 16.6 m.

Comment 1D

Does the parachute tumble? If yes, what is the frequency?

To provide a comprehensive response to this question, we conducted additional experiments to study the lateral movements during fall of our kirigami-inspired parachutes Designs A and B. For this purpose, we conducted drop tests using a small 6-axis accelerometer (AX6 from Axivity) mounted on a bottle of water attached to the parachutes' center as presented in **Comment 1B**. We launched the parachutes indoors from a height of 14.9 m and recorded the linear accelerations, $\ddot{x}$, $\ddot{y}$, and $\ddot{z}$ at a sampling rate of 200 Hz (note that the z-axis of the accelerometer was positioned opposite to gravity). Figs. R3a-b show the magnitude of the lateral acceleration, i.e., $\sqrt{\ddot{x}^2+\ddot{y}^2}$, as a function of time from launch to landing for three fall tests with Designs A and B. For Design A deforming in the cylindrical mode $\mathcal{C}$, no distinct pattern emerges in the signal to measure frequency (see Fig. R3a). On the contrary, for Design B deforming in the kirigami mode $\mathcal{K}$, we see a distinct frequency emerging (see Fig. R3b). To extract the tumbling frequency from the raw accelerometer data, we used the autocorrelation function:

$$R(\tau) = \frac{1}{N-\tau}\sum_{t=0}^{N-\tau-1} \ddot{r}(t)\cdot\ddot{r}(t+\tau), \qquad [R1]$$

where $\ddot{r} = \sqrt{\ddot{x}^2+\ddot{y}^2}$, N is the total number of samples, and τ is the time lag, which represents the amount by which a time series is shifted or delayed when comparing it to itself during the computation of autocorrelation. To determine the frequency of a signal using this method, we computed the $R(\tau)$ for different values of τ and identified the highest peak following the initial maximum at $\tau = 0$. This peak represents the fundamental periodicity of the signal, as it indicates the time shift at which the signal is most correlated with itself. By applying this method to each of the three tests conducted on Design B, we find frequencies of 1.40 Hz, 1.39 Hz and 1.48 Hz for a mean frequency of 1.42 Hz. Simplifying the problem to the swing of a simple gravity pendulum with frequency equal to $f_p = \frac{1}{2\pi}\sqrt{\frac{g}{l_p}}$, with g the acceleration of gravity and l_p the length of the pendulum which we assume is of the same order as the disk radius, i.e., $l_p = r_0 = 0.215$ mm, we find $f_p = 1.08$ Hz which is very close to the measured value of $f = 1.42$ Hz.

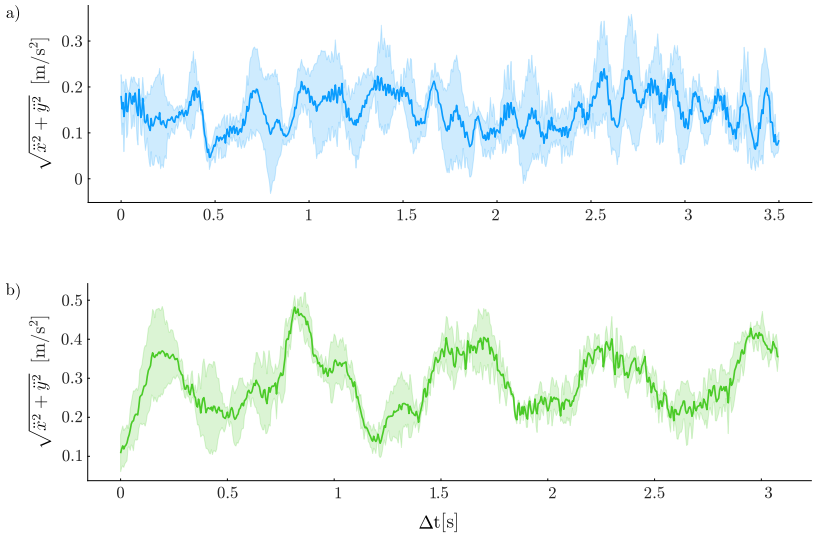


Fig. R3. Magnitude of the lateral acceleration $\sqrt{\ddot{x}^2+\ddot{y}^2}$ as a function of time during fall. (a) Results for Design A deforming in the cylindrical mode $\mathcal{C}$. (b) Results for Design B deforming in the kirigami mode $\mathcal{K}$. The lines and shaded areas are the average and standard deviation of three fall experiments.

To take into account this comment, we have added Fig. R3 and the following text in section S3. Experiments which is reproduced below for completeness

"**D. Tumbling of kirigami-inspired parachutes**

To investigate the tumbling frequency of our parachute, we conduct drop tests for parachutes with Designs A and B cut patterns. The parachutes are manufactured from a 0.311 mm thick shim with outer radius of $r_o = 215$ mm and

inner radius of $r_i = 21$ mm. We attach a 6-axis accelerometer (Ax6 rom Axivity) on a bottle of water mounted on the center of the parachutes and drop them indoor from a height of 14.9m while measuring their linear accelerations, $\ddot{x}$, $\ddot{y}$, and $\ddot{z}$ at a sampling rate of 200 Hz. Fig. R3 shows the magnitude of the lateral acceleration, i.e., $\sqrt{\ddot{x}^2 + \ddot{y}^2}$, as a function of time during the fall. For Design A deforming in mode $\mathcal{C}$ (blue curve in Fig. R3a), no distinct pattern emerges in the signal. On the contrary, for Design B deforming in mode $\mathcal{K}$ (green curve in Fig. R3b), we see a distinct frequency emerging. To extract the tumbling frequency from the raw accelerometer data, we use the autocorrelation function:

$$R(\tau) = \frac{1}{N-\tau} \sum_{t=0}^{N-\tau-1} \ddot{r}(t) \cdot \ddot{r}(t+\tau), \qquad [R2]$$

where $\ddot{r} = \sqrt{\ddot{x}^2 + \ddot{y}^2}$, N is the total number of samples, and τ is the time lag. To determine the frequency of a signal using this method, we computed the $R(\tau)$ for different values of τ and identify the highest peak following the initial maximum at $\tau = 0$. This peak represents the fundamental periodicity of the signal, as it indicates the time shift at which the signal best aligns with itself. By applying this method to each of the three tests conducted on Design B, we find tumbling frequencies of 1.40 Hz, 1.39 Hz and 1.48 Hz for an average frequency of 1.42 Hz. Simplifying the problem to the swing of a simple gravity pendulum with frequency equal to $f_p = \frac{1}{2\pi}\sqrt{\frac{g}{l_p}}$, with g the acceleration of gravity and l_p the length of the pendulum which we assume is of the same order as the disk radius, i.e., $l_p = r_0 = 0.215$ mm, we find $f_p = 1.08$ Hz which is very close to the measured value of $f = 1.42$ Hz. We hypothesize our kirgiami parachutes deforming in mode $\mathcal{K}$ sways at frequency $f \sim \frac{1}{2\pi}\sqrt{\frac{g}{r_o}}$."

Comment 1E

Where do they land compared to the vertical to the origin of flight?

Additional experiments regarding the distance between the parachutes landing spot and their initial release position were conducted and are presented in **Comment 1B**.

Comment 1F

What happens if there is some side wind?

In the presence of side wind, the parachute and its payload will be advected and drift roughly at wind speed. Our parachutes are "ballistic" in the sense that they are unguided and passive. Any such ballistic parachute will drift at wind speed plus any random deviation that might arise from instability or tumbling.

Comment 1G

What happens if the payload is distributed differently than attached in the middle?

While the problem of setting up the payload off-centered could lead to interesting behaviors, the goal here is to provide an easy to manufacture stable parachute. Installing the payload in the center is a simple and repeatable way to do so, whereas off-centering the payload might not be as straight-forward. However, from our understanding, the parachute will adopt a slight angle of attack as it reaches an angular equilibrium between the moment around the center of pressure of the parachute generated by the eccentric mass and the aerodynamic moment.

Comment 1H

Can these parachutes achieve something exciting that a regular parachute could not do?

First, conventional parachutes require a gliding angle for vertical stability (6, 7). Without onboard control, their landing position compared to the origin of the flight is difficult to predict. To highlight this, we performed the same drop experiments as presented in **Comment 1B** on a elliptical conventional parachute. The parachute was manufactured by *Fruity Chutes* with $r_o = 195$ mm, $r_i = 24$ mm and a drag coefficient $CD = 1.5$. Fig. R4b shows the distribution of the lateral displacements for the conventional parachute dropped 8 times. The results show a large discrepancy with maximum lateral displacement of 10.1 m. In comparison, our kirigami parachutes fall straight down and close to the landing target, regardless of the release angle (see Fig. R1c). This is exciting for humanitarian airdrop applications where one could predict more accurately the landing of emergency supplies. In addition, we expect that by extending our geometrical parameter space, e.g., investigating asymmetric, chiral or hierarchical kirigami patterns, could enable us to program the fall trajectory of parachutes. However, this is beyond of the scope of the current research. To account for this comment, we have added Fig. R4 and the following text in Section S3. Experiments, which is reproduced below for completeness.

"**Drop testing of a conventional parachute**
To compare the behavior of our kirigami-inspired parachutes to a conventional parachute, we conduct similar drop

experiments to the ones we conducted on Designs A and B cut patterns. We use a conventional elliptical parachute manufactured by *Fruity Chutes* with $r_o = 195$ mm, $r_i = 24$ mm and a drag coefficient of $CD = 1.5$. First, the parachute is dropped indoor from a height of 14.9 m, while being equipped with a 6-axis accelerometer (AX6 from Axivity). The accelerometer measures the parachute's vertical acceleration $\ddot{z}$ at a sampling rate of 200 Hz. Fig. R4a shows the vertical acceleration measured over three tests as a function of time (solid curve). We observe that the conventional parachute descends with an unsteady vertical acceleration, similarly to Design A deforming in mode $\mathcal{C}$. By integrating the average of the vertical acceleration $\ddot{z}$, we can obtain the vertical velocity $\dot{z}$ over time (dashed curve in Fig. R4a). The terminal velocity of the conventional parachute is calculated as -4.66 m/s. In Fig. R4, we report the lateral displacement of the fall across eight drop tests. We find a large discrepancy with one parachute falling more than 10 m away from the target."

In addition, we have added the following text in the *Conclusions and outlook*:

"While this study focuses on the closed-loop kirigami pattern, expanding the geometrical parameter space to other designs such as asymmetric, chiral or hierarchical patterns, could enable programming the entire fall trajectory of parachutes."

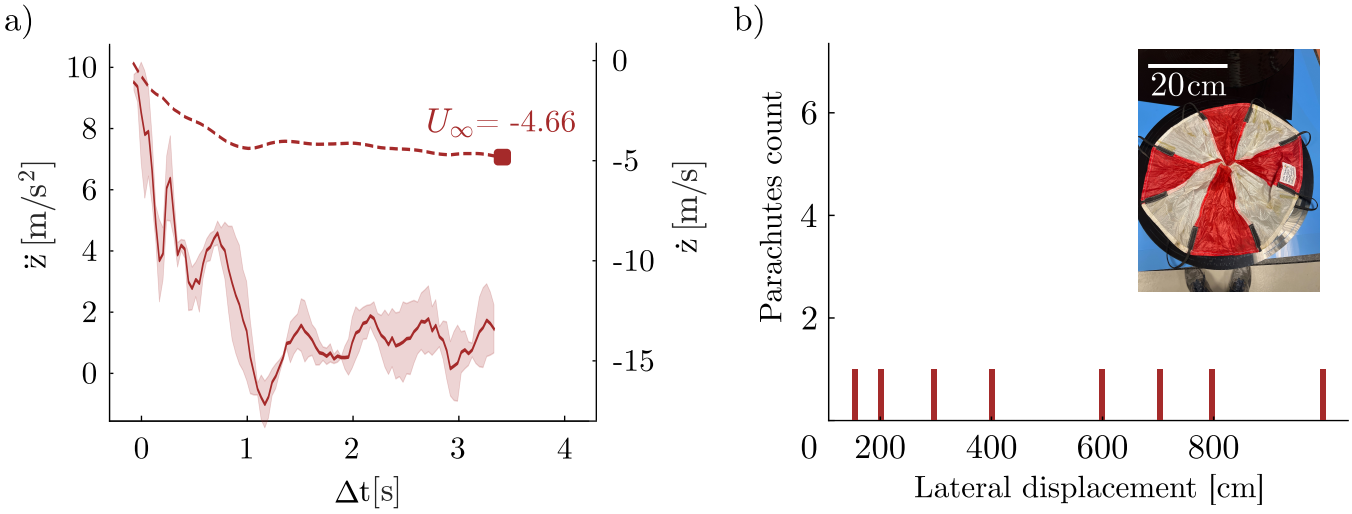


Fig. R4. Performance of a conventional parachute. a) Vertical acceleration, $\ddot{z}$, and velocity, $\dot{z}$, of the conventional parachute. The solid line and shaded area are the average and standard deviation of the vertical acceleration of three fall experiments measured with an accelerometer. The dashed line is the vertical velocity obtained by integrating numerically the mean vertical acceleration of three fall experiments. b) Lateral displacement of the conventional parachute across multiple drop test. Inset shows the parachute by *Fruity Chutes*.

Comment 1I

I would suggest, for example, stacking many disks (10-100) and dropping them at once from a drone or something of the like. These disks could be identical or even better different (2 populations), e.g., allowing them to sort themselves during the fall.

We thank the reviewer for their suggestion. Following their recommendation, we conducted additional experiments to observe the behavior of two different populations of kirigami-inspired parachutes during mass drop tests. For this purpose, we attached ten parachutes to individual ropes held together to ensure a simultaneous release of all the parachutes. The ten parachutes consisted in five parachutes Design A (deforming in mode $\mathcal{C}$) and five parachutes Design B (deforming in mode $\mathcal{C}$). We launched the parachute indoors from a height of 16.6 m and filmed their descent. As a result, we observed that the two populations sorted themselves as suggested by the reviewer. At the front, the five parachutes Design B synchronized their steady descent, while behind, the five parachutes Design A followed at random. To show the results, we added Movie S5 *Mass dropping of two different populations of kirigami-inspired parachutes* to the Supplementary Information, and mentioned in the conclusion the potential use of multiple patterns.

"Additionally, using multiple patterns of our kirigami-inspired parachute in a single launch could be used to sort out different populations during flight (see Supplementary Movie S5 (5))."

Comment 1J

The manuscript could also benefit from an explicit discussion of the limitations of this approach. Could we go bigger? How would these contraptions compare with regular parachutes?

We thank the reviewer for their input. To take into account the comment and highlight the limitation of our manufacturing approach, we have added the following text in the *Conclusions and outlook* section:

"We note that our parachute's main advantage is the improved stability in comparison to conventional parachutes which could be useful for humanitarian aid delivery. Scaling up our manufacturing process without requiring manual assembly (see Fig. S2) would be possible via industrial size laser cutters and cutting dies."

Comment 1K

In conclusion, I find the idea beautiful but would like to see the concept pushed further before I can recommend publication.

We hope the new set of experiments, shinning lights on our kirigami parachute kinematics, distance from targets, tumbling frequency, and self-sorting capability will have pushed our concept further.

Response to reviewer #2

Key results: This work studies how kirigami structures change shape amidst fluid flow. It uses kirigami cuts to manufacture parachutes. The kirigami patterns can be laser cut into a disk which deploys into a parachute shape upon falling through air. The kirigami patterns are not new - there is no attempt to design them for this purpose, or indeed optimize them. The paper has simulation, experimental, and analysis components which generally agree. The authors build a meter-scale kirigami parachute and find that it can help an object maintain a more vertical trajectory when drifting to the ground, and that it slows the fall down.

We thank reviewer #2 for their review and overall assessment of our manuscript.

Comment 2A

The kirigami parachute is theoretically easier to manufacture than a conventional parachute because it uses lasercuts instead of seams and folds. However, it is almost certainly true that the cuts will grow and might fail catastrophically - so likely this can be used once - which is quite wasteful compared to parachutes.)

Multiple drop tests were conducted to measure the vertical acceleration of the parachutes (see **Comment 1B**). Each parachute was dropped at least three times from a height of 14.9 m with a payload of 144 g and remained intact. Additionally, a large amount of tests were carried out on other parachutes to observed their lateral drifts (see **Comment 1B**). Again, no parachutes were damaged during the multiple drop tests. Therefore, we anticipate our parachute can be used more than once.

Comment 2B

The large demo parachute in this paper still has pieces which must still be taped together, and this is not scalable.

We thank the reviewer for their comment. On the one end, it is true that, based on our manufacturing technique, kirigami parachutes with a diameter larger than the laser cutter bed require manual assembly (see Fig. S2). Other methods, such as using large dies or industrial sized laser cutters could be exploited, but this falls out of the scope of the current study. On the other hand, conventional parachute manufacturing still requires a lot of manual labor done by skilled workers when it comes to sewing and assembling the parachutes, which is comparable to our current technique. To take into account the comment and highlight the limitation of our manufacturing approach, we have added the following text in the *Conclusions and outlook* section:

> "We note that our parachute's main advantage is the improved stability in comparison to conventional parachutes which could be useful for humanitarian aid delivery. Scaling up our manufacturing process without requiring manual assembly (see Fig. S2) would be possible via industrial size laser cutters and cutting dies."

Comment 2C

The kirigami parachutes slow the terminal velocity comparably to conventional parachutes in a low load-to-area ratio regime. It looks like conventional parachutes begin outperforming the kirigami parachutes at about 2.25lbs to m^2 weight to area ratio ($10N/m^2$).

We agree with the reviewer that conventional parachutes outperform our kirigami parachutes at about about 2.25lbs to m^2 weight to area ratio ($10N/m^2$) in terms of terminal velocity. However, conventional parachutes require a gliding angle for vertical stability (6, 7). In comparison, our kirigami parachutes fall straight down and close to an intended landing target (see the comparison between conventional and kirigami parachutes in Figs. R1 and R4) of the response.

Comment 2D

The topic and potential application of this work are interesting but not particularly surprising. Streamlining parachute manufacturing improves their potential for airdropping items to people. Additionally, fluid interaction behavior is a potentially interesting area of the kirigami materials field.

We thank the reviewer for their understanding of our work. The novelty here is the application of these fluid-structure interactions to the parachuting field. We refer to **Comment 1A** for a clarification about the novelty of our work.

Comment 2E

The potential noteworthiness of this paper comes from the kirigami parachute application, which is very limited in its applicability. Kirigami parachutes perform comparably to conventional parachutes only for small weight to area ratios, which is interesting but not remarkable. The demo parachute in this paper also still needs to be pieced together with seams, and is not yet easier to manufacture than a conventional parachute. The other findings in this paper are nice, but not significant relative to advances in kirigami technology, so the parachute demonstration falls a little flat.

The novelty with our parachutes is not an improvement on falling velocity, but rather the added stability. We have characterized the performance of our kirigami parachutes by performing additional experimental tests to measure their free fall kinematics, distance from targets, tumbling frequency, and self-sorting capability. The reviewer is referred to **Comments 1B**, **1D**, **1H**, and **1I** for details.

Comment 2F

Falling disks and wind tunnel experiments: These experiments show that there is a regime of kirigami cut patterns in a disk which causes a large z-axis extension ("Mode K") and improved stability when the disk falls. The authors should address more clearly why Design A and other patterns could lack a Mode K. There's a discussion on line 287 which says the extension limit of Design A's Mode C is given by r_0 - r_1, but why does Design A not have a Mode K at all, even at higher flow velocities? Visually, it seems the reason is geometric.

We approach the distinction between mode $\mathcal{C}$ and mode $\mathcal{K}$ through the use of our linear transition criteria. The geometric explanation the reviewer discusses is linked to the geometric pattern, which influences the dimensionless stiffness $\bar{K}$, which is directly related to our transition criteria. A clarification regarding this has been added after the introduction of the transition criteria in the *Results* section:

> "This modeled pattern's added stiffness can be used to define a linear transition criterion: when mode $\mathcal{K}$ is softer than mode $\mathcal{C}$, then mode $\mathcal{K}$ prevails. We find that this stiffness criterion scales as $\bar{K} \leq 28$ (see section S5D (43) for more details regarding the transition criterion)."

Comment 2G

Fig. 1b-d is a nice visualization of what the different trajectories look like. In some locations 1e is said to display the standard deviation of displacement, while in other locations it says "Lateral displacement" (in-figure x-axis label on Fig. 1e, combined with the first sentence in the caption "Lateral displacement as a function. . . "). It's confusing, and it would be good to make it clear that the standard deviation is being plotted.

We changed the caption to represent the fact that three standard deviations are plotted. However, the label of the x-axis is not changed as the lines represent three standard deviations, not the axis itself. The caption now reads:

> [...] e) Three standard deviations of the lateral deviation [...].

Comment 2H

The "cylindrical mode C" the authors describe is not really a cylinder, as the ends wrapping around the cylinder never turn back inward.

Here we use this term as it is referred to in that manner in the literature in Schouveiler and Eloy, 2013 (32). A clarification has been added to the text.

> [...] into a cylindrical mode as described by Ref. (32) (referred to as mode $\mathcal{C}$) which is reminiscent of a draping disk under flow (32, 40).

Comment 2I

Simulation framework: The simulation results agree nicely with the experiments above.

We thank the reviewer for their appreciation of our simulations.

Comment 2J

Parachute demonstration: The kirigami parachute slows the fall down to about 40% of free fall velocity (line 616, 673). There are terminal velocity vs. W/A curves for winged seeds and for an ideal parachute. The colored points in Fig. 4a should be the kirigami parachutes, but what do the different colored markers mean?

The colored markers refer to the previously used colors in Fig. 3a. A mention has been added to the caption.

> [...] (colored markers, with the same colors that were used in Fig. 3a).

Comment 2K

What are the authors saying in line 586?

Line 586 refers to the following:

> "However, these natural flyers and our kirigami disks underperform conventional parachutes at high W/A as the latter are typically modeled using $W = \rho U_\infty^2 A C_D/2$, which leads to $U_\infty = (2W/\rho A C_D)^{1/2} = 1.5(W/A)^{1/2}$ using the rigid disk from our experiments as example, with $C_D = 1.26$ the drag coefficient obtained experimentally and $\rho = 1.225\,\mathrm{kg\,m^{-3}}$ the density of air."

Here, we explain that the conventional parachutes follow the usual drag law (rigid drag), whereas natural flyers and kirigami parachutes follow a drag law that modified due to reconfiguration in the case of kirigami disks. We reformulated this sentence to make it clearer.

> "However, these natural flyers and our kirigami disks underperform conventional parachutes at high W/A as the latter are typically modeled using $W = \rho U_\infty^2 A C_D/2$. This typical drag law leads to $U_\infty = (2W/\rho A C_D)^{1/2}$, which, when using the rigid disk from our experiment, the terminal velocity is described as $U_\infty = 1.5(W/A)^{1/2}$, since $C_D = 1.26$ the drag coefficient obtained experimentally and $\rho = 1.225\,\mathrm{kg\,m^{-3}}$ the density of air."

Comment 2L

Was the water bottle or camera damaged after landing with the kirigami parachute?

The water bottle and camera were undamaged after the landing of the large kirigami-inspired parachute. Additionally, multiple drop tests were conducted indoor using an accelerometer and a bottle of water (see **Comment 1B**). Both remained intact throughout all tests.

Comment 2M

In Fig. 4a, the kirigami parachute is comparable in slowing the fall to a conventional parachute in a certain regime (up to around 10^1 N/m^2). Is this a realistic regime for airdrops of helpful items? Where on this graph would the water bottle experiment fall (both predicted and experimental results)?

We thank the reviewer for noting this regime. Reaching a regime of $W/A < 10\,\mathrm{N\,m^{-2}}$ is possible by adjusting the parachute's area, but it is rarely required. By accepting to drop items slightly faster, smaller parachutes can be used while maintaining the improved stability. Again, here, our parachutes do not aim to compete with conventional parachutes regarding their terminal velocity, but their improved stability. A clarification regarding this topic has been added towards the end of the *Results* section.

> "The predicted and experimental terminal velocity of the meter-scale parachutes are added as a comparison in Fig. 4a to show that the parachute remains on the same line as the tested kirigami disks.

Regarding the water bottle's performance, we added it to Fig. 4a (see Fig. R1a above for details).

Comment 2N

The authors should provide more clarity on how accurately the theoretical transition model can predict whether a cut pattern deforms into mode C or K. In the current text, it seems like the simulations are only accurate when the deformation mode is already known.

The theoretical transition model's accuracy is illustrated within Fig. 3b, such that most parachutes follow the transition criterion. Numerically speaking, due to the cost of running these simulations, few different geometries were run, but the numerically observed behavior was always accurately simulated with no input on our end. A precision regarding this has been added in the text in the *Results* section.

> "It is important to note that the simulations did not take the deformation mode as an input, yet they accurately predicted the deformation mode in all cases we tested.

Comment 2O

The authors claim the kirigami parachutes can offer stability "without consideration of the initial release orientation". Is this supported anywhere?

The impacts of the initial release orientation on our kirigami-inspired parachutes were further investigated and are presented in **Comment 1B**. Especially, we refer the reviewer to the results of Fig. R1c and Fig. R4.

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Kirigami-inspired parachutes with programmable reconfiguration
Manuscript number: 2024-07-13735C

Danick Lamoureux[a], Jérémi Fillion[a], Sophie Ramananarivo[b], Frédérick P. Gosselin[a,c], and David Melancon[a,c]

a. Laboratory for Multi-Scale Mechanics (LM2), Department of Mechanical Engineering, Polytechnique Montreal, 2500 chemin de Polytechnique, Montreal (Quebec), H3T1J6, Canada;
b. LadHyX, CNRS, École Polytechnique, Institut Polytechnique de Paris, 91120, Palaiseau, France
c. Research Center for High Performance Polymer and Composite Systems (CREPEC), Department of Mechanical Engineering, McGill University, 817 rue Sherbrooke Ouest, Montréal, Québec H3A 0C3, Canada

Response to Reviewer #3

The authors describe a novel parachute design, made by placing azimuthal cuts in a thin plastic sheet (fig 1). The effect of the cut pattern on aerodynamic behaviour is measured and simulated with a recently introduced toolkit (fig 2,3). Experimental results for two cut patterns are obtained and compared to air-dispersed seeds and ideal parachutes (fig4). A metre-scale sample is produced and used to safely deposit a water bottle from around 60m elevation (fig5).

The concept of shape-morphing kirigami and the study of its behaviour under flow is not new. However, this work provides an important advancement: it demonstrates how to translate previous theoretical work into a practical application. I believe that this is a necessary and broadly welcomed development in the field of architected structures. In addition, the experimental, theoretical, and numerical work are well carried out and reported.

We thank Reviewer #3 for their insightful comments and appreciation of our work. Please see below our point-by-point response.

Comment 3A

That said, the manuscript would benefit from a sharper narrative and updated figures. The parachute application is central to the work's importance. The authors show that, at low load-to-area ratios, kirigami parachutes can match the typical terminal velocity of conventional ones, and improve control over lateral drift. However, this result is not clearly stated in either the abstract, the introduction, fig. 4, or the discussion around fig 5, and is only partially addressed in the conclusions. I would recommend that the authors update the manuscript to help understand readers what is being achieved here (matching terminal velocity and improved lateral precision).

We agree with the Reviewer that we should clarify the advantages of our kirigami-inspired parachute over conventional ones. Fig. 4a shows that at high load-to-area ratios W/A the terminal velocity of conventional parachutes is lower compared to our kirigami-inspired parachutes.

However, at low W/A, our kirigami parachute can match conventional ones in terms of terminal velocity. First, we have modified our abstract to highlight the advantage of kirigami-inspired parachutes over conventional parachutes. It now reads as:

> "The art of kirigami allows programming a sheet to deform into a particular manner with a pattern of cuts, endowing it with exotic mechanical properties and behaviors.[1-17] Here we program disks to deform into stably falling parachutes as they deploy under fluid-structure interaction. Parachutes are expensive and delicate to manufacture, which limits their use for humanitarian airdrops or drone delivery. Laser cutting a closed-loop kirigami pattern[18] in a disk induces porosity and flexibility into an easily fabricated parachute. By performing wind tunnel testing and numerical simulations using a custom flow-induced reconfiguration model[19], we develop a design tool to realize kirigami-inspired parachutes. Guided by these results, we fabricate parachutes from the centimeter to the meter scale and test them in realistic conditions. We show that at low load-to-area ratios, kirigami-inspired parachutes exhibit a comparable terminal velocity to conventional ones. However, unlike conventional parachutes that require a gliding angle for vertical stability[20] and fall at random far from a target, our kirigami-inspired parachutes always fall near the target, regardless of their initial release angle. These kinds of parachutes could limit material losses during airdropping as well as decrease manufacturing costs and complexity."

Second, we have added the results of Fig. S9 in Fig. 4c to clarify the utility of a kirigami-inspired parachute. The updated Fig. 4 is reproduced below as **Figure 1** for completeness.

Third, we have further highlighted the benefits of our parachutes in the discussion around Fig.4:

> "Ref. 21 found different scaling laws, as identified in Fig.4a, for the flying seeds, where we happen to fit the most efficient trend, as $U_\infty = 1.05(W/A)^{2/3}$. These natural flyers and our kirigami disks match conventional parachutes at low W/A as the latter are typically modeled using $W = \frac{1}{2}\rho U_\infty^2 A C_D$. This typical drag law leads to $U_\infty = (2W/\rho A C_D)^{1/2}$, which, when using the rigid disk from our experiment, the terminal velocity is described as $U_\infty = 1.5(W/A)^{1/2}$, since C_D=1.26 the drag coefficient obtained experimentally and ρ =1.225 kg/m^3 the density of air. While for high W/A, conventional parachutes achieve a lower terminal velocity compared to our kirigami disks, they require a gliding angle for vertical stability.[20]"

Finally, we have modified the conclusion to emphasize the benefits of our concept:

> "In addition to being easy to fabricate, our parachute reduces lateral displacement during descent, unlike conventional designs that often drift randomly and far from an intended target. This could be especially useful for humanitarian aid delivery."

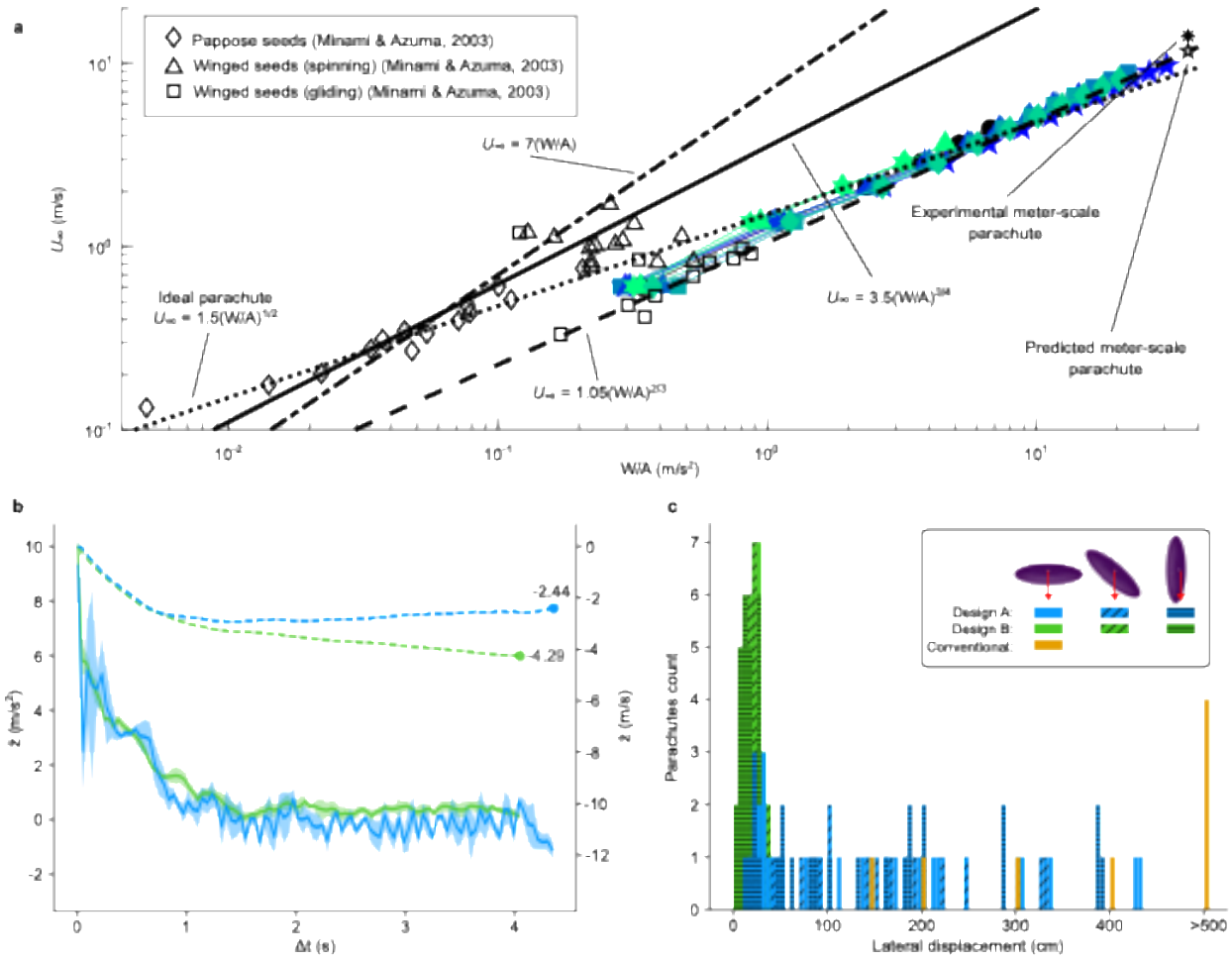


Figure 1. Performance of kirigami-inspired parachutes. a. Terminal velocity U_∞ as a function of load per unit of area W/A for different species of wind-dispersal seeds[21] and our kigirami-inspired parachutes (colored markers, with the same colors that were used in Fig.3a). The lines are trends and fits identified by Ref. 21, with the black dotted line the relationship of an ideal parachute. The black asterisk and star are the experimental and predicted terminal velocities of the meter-scale parachute discussed in this work. **b.** Vertical acceleration, $\ddot{z}$, and velocity, $\dot{z}$, of kirigami-inspired parachutes Designs A and B (blue and green, respectively). The solid lines and shaded areas are the average and standard deviation of the vertical acceleration of three fall experiments measured with an accelerometer. The dashed lines are the vertical velocity obtained by integrating numerically the mean vertical acceleration of three fall experiments. **c.** Lateral displacement across multiple drop tests of kirigami-inspired parachutes Designs A and B as well as a small-scale elliptical parachute (orange bars) manufactured by Fruity Chutes with r_o=195 mm, r_i=24 mm, and a drag coefficient of C_D = 1.5 (see Methods). The solid bars represent parachutes launched at 0°, the hatched bars at 45°, and the horizontally bars at 90°.

Comment 3B

fig 2c—e, fig3a, fig3c: are error bars included here and simply not visible?

As mentioned in the legend of Fig. 2, the experimental data from Fig. 2c-e and Fig. 3c are the average value of the tests performed in the wind-tunnel over a period of 30s. The experimental data from Fig. 3c is the initial slope of tensile test on the kirigami disks. As reported in Extended Data Fig. 4, there is very little discrepancies between runs, and we report here only the average value. It is important to note that the experimental error induced by the manufacturing of our specimens, the wind-tunnel experiment, and tensile testing do not change the conclusions of our

study as we showed that by conducting dimensional analysis, our experimental results collapsed unto a master curve that is aligned with our numerical prediction (see Figs. 3c-d). To account for the Reviewer's comment, we include all wind-tunnel and tensile testing raw data as Supplementary Data.

Comment 3C

line 303: please refer to the SI equation or section where the added stiffness is defined.

A reference to Supplementary Methods Section S2B has been added in the main text where the added stiffness is defined.

Comment 3D

line 310: is the choice of 28 for the stiffness criterion an ad hoc one to separate the populations in fig.3b? Please add an explanation in the SI.

The choice of $\overline{K} \leq 28$ for the transition criteria is purely based on observations, as it seems to separate relatively well the two populations. A small clarification has been made in the main text.

> "We find that this stiffness criterion scales as $\overline{K} \leq 28$, which is identified empirically [...]"

Comment 3E

line 614: "stability": does this refer to lateral displacement, vibration sensitivity, or something else?

We have modified the text around line 614 to take into account the Reviewer's comment. It now reads:

"In addition to being easy to fabricate, our parachute reduces lateral displacement during descent, unlike conventional designs that often drift randomly and far from an intended target. This could be especially useful for humanitarian aid delivery."

Comment 3F

fig 4b: including the results of fig. S9 here would be very helpful to clarify the utility of a kirigami parachute.

We agree with the Reviewer, and we have added the results of Fig. S9 to Fig. 4b. Please see **Comment 3A**.

Comment 3G

line 852: please provide a rough estimate for the observed lateral displacement of the parachute.

As discussed in our first response to the reviewers, in the presence of side wind, any parachute and its payload will be advected and drift roughly at wind speed. Our parachutes are "ballistic" in the

sense that they are unguided and passive. Any such ballistic parachute will drift at wind speed plus any random deviation that might arise from instability or tumbling. Therefore, the results highly depend on wind condition which we did not characterize during our outdoor experiments. To provide a rough estimate of the lateral displacement during the launch from the drone, we used the footage from the GoPro that was attached directly to the parachute. At launch, the parachute was near the 24-yard line and upon collision with the ground, it reaches the 32-yard line. This gives an estimated lateral displacement of about 7 m for a fall of 60m. To consider this comment, we have modified the text in the Methods section as:

> "We note that winds were present during testing, causing relatively important lateral accelerations that are not modeled in our simulations. These winds caused angular vibrations of the water bottle, which were damped by the parachute's interaction with the flow. Nevertheless, the kirigami-inspired parachute fell vertically and did not deviate substantially from its axis (we estimated a lateral displacement of about 7 meter over the 60-meter free fall based on the GoPro attached to the parachute, see Supplementary Movie S4)."

Comment 3H

line 14-15: ref. 19 looks at undesired motion of supersonic parachutes, which is not relevant here.

Ref.19 has been removed.

Comment 3I

line 25: "reduce the risk to human life" is not clearly motivated.

We agree with the Reviewer #3 that the statement is not clearly motivated. The last sentence of the abstract has been rephrased as:

"These kinds of parachutes could limit material losses during airdropping as well as decrease manufacturing costs and complexity."

Comment 3J

line 20: "closed-loop" is confusing here, please add a citation or omit the term.

The term closed-loop kirigami is standard in the community. We have added the proper reference to the abstract.

Comment 3K

line 48: ref. 39 refers to an APS meetings abstract, please reformat citation.

This has been updated.

Comment 3L

Fig.1: panel b—d: adding a schematic at the top to illustrate the circular cutting patterns would be very helpful. Panel e: please add the complete lateral displacement data, or provide it in an SI figure.

We have added the schematic of the circular cutting patterns of Designs A and B as well as the complete lateral displacement data of Fig. 1e as Extended Data Fig. 1 (which is reproduced here for completeness as **Figure 2**.)

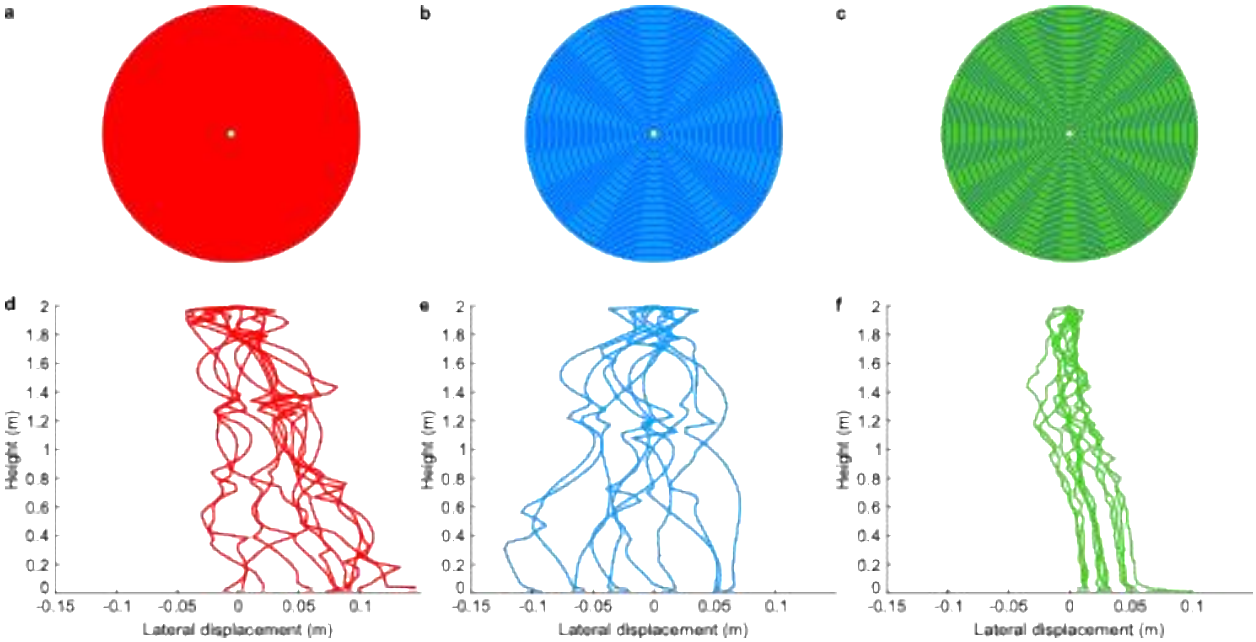


Figure 2. Lateral displacement of plain and kirigami disks during free fall. a. Plain circular disk. **b.** Cutting pattern of kirigami disk Design A. **c.** Cutting pattern of kirigami disk Design B. **d.** Lateral displacement as a function of vertical height during free fall for ten disks with no cuts (**d**), ten disks with cutting pattern Design A (**e**), and ten disks with cutting pattern Design B (**f**).

Comment 3M

line 111: please define U_∞ as the wind tunnel air flow speed here.

This has been updated.

Comment 3N

line 177: r_1 should be r_i.

This has been updated.

Comment 3O

line 303: please show the unity slope in fig. 3a.

This has been updated.

Comment 3P

in fig.3b, is the added stiffness measured or calculated?

The parameter $\overline{K}$ is always calculated in our study. A clarification has been made in the text to refer to the correct section in the Supplementary Methods. Please see **Comment 3C**.

Comment 3Q

if possible, add a legend instead of inserted labels in fig.4a.

We agree with the Reviewer that in its original version, Fig. 4a was cluttered. However, we have now formatted the Figures according to Nature's guidelines and the size of the inserted labels have reduced substantially, making it easier to read. Therefore, we decided to keep it as it is.

Comment 3R

SI: line 113-114: define exactly which deformation regime was used to fit the stiffness of the various samples. If possible, indicate this in fig. S4. Linear fit results can depend a lot on fitting regime, and it would be great to quantify this e.g. using error bars in fig. 3a.

To extract the experimental stiffness of the kirigami disks during tensile testing, we first used the function *ischange()* from Matlab to extract the linear part of the force and displacement curve. We then used the *polyfit*() function to interpolate a polynomial $p(x)$ of degree 1 that is a best fit (in a least-squares sense) for the data. Since the initial part of the force-displacement curves are quasi-linear, modifying the threshold parameter of the function *ischange*() produces little impact of the fitted value of K. In addition, as reported in Extended Data Fig. 4, there is very little discrepancies between runs. Therefore, we leave the average value in Fig. 3a and include the raw experimental data from the tensile tests as Supplementary Data (see **Comment 3B**).

Comment 3S

SI: line 225: "alpha" is mentioned but not defined.

We thank the reviewer for their attention to detail. There was indeed an error, such that α should be replaced by σ. The change has been added.

Comment 3T

SI: line 312: C_2 is not defined and may be mixed up with C_1.

We again thank the reviewer for catching this mistake. The text has been corrected as:

> *"*However, since we did not compute the required constants, and due to our many assumptions, these constants would not allow for an exact representation of reality, we can instead look for $\widetilde{K}/K_C=C_1$, with C_1 a constant. Therefore, we rather compute:

$$\frac{\widetilde{K}}{K_C} \sim \frac{B\overline{K}}{r_o^2}\frac{r_o^2}{B} = \overline{K} = C_2,$$

where C_2 is a constant."

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