

Design of an Origami-Inspired Deployable Aerodynamic Locomotive Fairing

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Abstract: *The design of an aerodynamic origami-inspired deployable fairing for locomotives is discussed. Because freight locomotives may or may not be in the lead position and the constrained space between coupled locomotives is small, it is desirable for the fairing to be stowed flat in the non-lead position. The resulting fairing is based on non-developable thick origami. Thick origami has traditionally been applied in the context of developable patterns. Considerations for applying thick origami to non-developable patterns is discussed. The fairing geometry is optimized using CFD analysis and multi-dimensional polynomial regression. Prototypes of the fairing are constructed to validate its operational feasibility. The fairing is estimated to reduce overall aerodynamic drag on the locomotive by 16% at a 80 kph velocity. This translates into an estimated fuel savings of over 24,000 liters of diesel annually per train retrofitted with the fairing.*

1 Introduction

Aerodynamic drag is one of the largest contributing factors to the fuel consumption of large vehicles at cruising speed. Large freight vehicles would benefit from aerodynamic improvements in their design but are often constrained by functional requirements such as accessibility and overall size.

Origami has been used as a source of inspiration in solving some of the most difficult space constrained problems ranging from space [Miura and Natori 85] to medical applications [You and Kuribayashi 09]. This project utilizes the principles of origami to create a transformable aerodynamic add-on device for locomotives. The device, which we will refer to as the fairing, can transform its shape from an aerodynamic form to a collapsed form so that the functional requirements of the locomotive are maintained. The basic concept of this reconfiguration is shown in Figure 1. The deployed configuration is meant to decrease pressure drag on the lead locomotive of a train. The stowed configuration is meant to allow coupling of locomotives without restricting the walkway between locomotives for when the locomotive is not in the lead position.

The fairing design is based on thick origami because the panel thickness must be accommodated to prevent self intersection of panels. Many techniques have been introduced which accommodate thickness in origami-based mechanisms [Lang

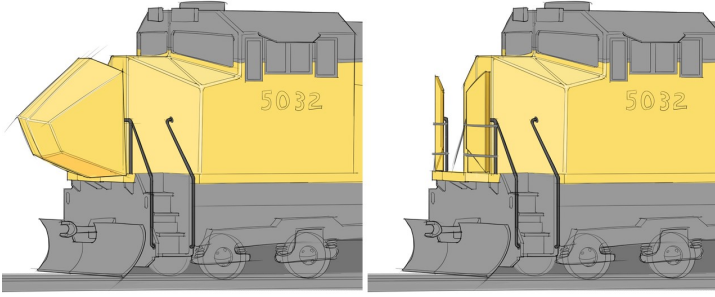


Figure 1: *Initial concept for an origami-inspired deployable fairing based on rigid folding panels. Left: The fairing in its deployed state. The shape should reduce aerodynamic drag. Right: the fairing in its stowed (folded) state. Open space must be maintained in the stowed space to accommodate a walkway between coupled locomotives.*

et al. 18]. These techniques include changing the shape of the panel to prevent intersection [Tachi 11, Edmondson et al. 16], moving the hinges of the pattern out of plane to prevent interference [Chen et al. 15], replacing revolute joints with flexible hinges that allow out of plane movement [Zirbel et al. 13, Pehrson et al. 16], and modifying the crease pattern to create space for stacking panels [Ku and Demaine 16].

The foldable fairing presented here is also based on non-developable origami. A developable surface is one where the Gaussian curvature is zero, i.e. it can be flattened into a plane without stretching the material. Because traditional origami starts with a flat sheet of paper and is folded into a 3D shape, it can likewise be unfolded back into a flat sheet and is therefore developable. In terms of origami, we define a developable pattern to be one that does not require cutting and gluing to achieve its final shape. Although cutting and gluing is typically eschewed in origami, in engineering design, some interesting and useful designs have come about by cutting and gluing paper to create non-developable patterns such as egg-box patterns [Xie et al. 15], tube patterns [Filipov et al. 16], and three-dimensional polyhedra-based patterns [Overvelde et al. 17]. Thickness-accommodation techniques have been applied primarily to developable patterns. This work explores the potential of thickness-accommodation techniques being applied to patterns that are non-developable. We will discuss the additional considerations that must be made when dealing with non-developable thick origami and the constraints that some techniques have with non-developable vertices.

This document outlines the approach taken and the results achieved to design a foldable locomotive fairing based on non-developable thick origami that can meet the general requirements of both the deployed and stowed states. Additional con-

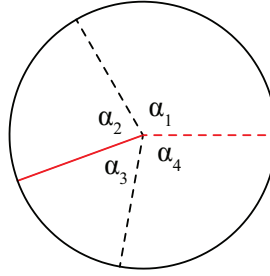


Figure 2: A degree-4 vertex.

straints and functional requirements that the design must achieve are discussed. The final fairing design is shown to meet the space constraints, functionality requirements, and decrease aerodynamic drag by over 16 percent.

2 Background

The block-like shape of modern freight locomotives makes for poor aerodynamics when compared to the shape of high-speed passenger trains [Lukaszewicz 07]. The design of today's locomotives has been driven largely by operational constraints and cost to manufacture rather than its aerodynamic performance. The resulting locomotive shape is unfortunate because it results in high aerodynamic drag and contributes to higher fuel consumption at cruising speed.

The attachment of a nose fairing to a locomotive could reduce the total drag on a train. However, for such an attachment to work with current locomotives, it must not interfere with the locomotive coupling function. Locomotives are often coupled at the front and rear of a long train. A large static fairing would need to be removed anytime it was not on the leading locomotive.

Freight locomotives have features that constrain the fairing, including windshields, headlights, front door, stairs, walkway, coupler, snow plow, hand rails, and electrical and pneumatic connectors. The foldable fairing presented here seeks to overcome the challenges inherent with a static fairing by providing stowed and deployed configurations that can meet the requirements of both the lead and non-lead locomotive positions.

2.1 Thick Origami

An origami pattern can be seen as a system of spherical linkages where panels are links and fold lines are hinges [Bowen et al. 13, McCarthy and Soh 10]. Rigidly-foldable origami patterns do not require the bending of facets while folding and only require deflection of the creases to fold. When modeled as a linkage these patterns will have a positive mobility. Using rigidly foldable patterns in thick origami ensures that strain energy is not stored in panels and the mechanism will be easier to actuate.

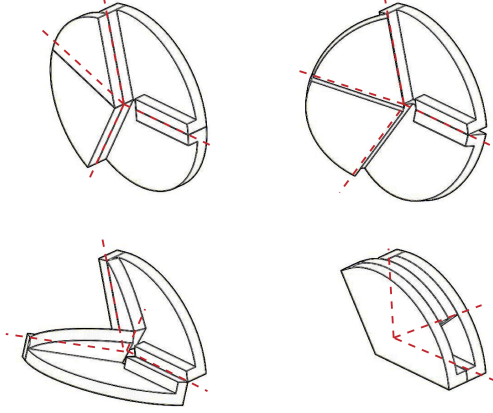


Figure 3: An example offset-panel vertex. Hinges are indicated by red dashed lines.

The degree-4 vertex, such as the one shown in Figure 2, is the building block of many origami patterns. The angles between fold lines are called sector angles and are represented by α_1 through α_4 . For a degree-4 vertex to fold flat it must satisfy the Kawasaki-Justin theorem [Demaine and ORourke 07] which states that for flat-foldable vertices:

$$\alpha_1 - \alpha_2 + \alpha_3 - \alpha_4 = 0. \quad (1)$$

When paper is creased, its stiffness is reduced along the crease line allowing the paper to act as both the links and hinges in a mechanism [Francis et al. 13]. When designing thick origami mechanisms, the crease lines of an origami pattern are replaced by a surrogate hinge [Delimont et al. 15]. These hinges can be revolute joints, compliant members, or rolling-contact-based joints [Lang et al. 17]. For the locomotive fairing, the load carrying capacity of the hinges is an important consideration. The wind load that a fairing experiences during operation translates into large forces so traditional pin-joint hinges are used in the fairing design.

Thickness-accommodation techniques considered for use in the foldable fairing include the hinge-shift technique [Chen et al. 15] and the offset-panel technique [Edmondson et al. 16]. These techniques are chosen due to the fact that flat panels are used in their construction, special hinges or an extra number of hinges are not required, and revolute joints can be used.

The offset-panel technique accommodates thickness through the use of panels that are offset from the zero-thickness origami pattern but maintain the same hinge locations as the zero-thickness origami pattern. An example degree-4 offset panel vertex is illustrated in Figure 3 where the hinge lines intersect at a point, maintaining the same spherical linkage as the original origami pattern. The offset panel technique has been utilized in various thick origami applications [Morgan

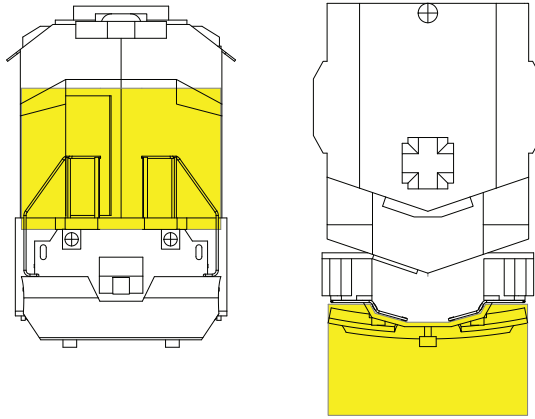


Figure 4: Design volume for the deployed fairing. Usable area is highlighted in yellow.

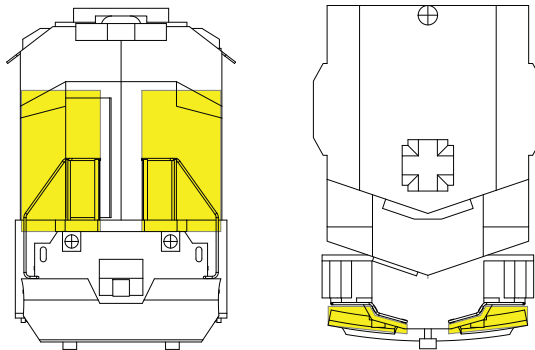


Figure 5: Design volume for the fairing in the stowed configuration. Usable area is highlighted in yellow.

et al. 16], however the application of the technique to non-developable patterns is a new area of exploration. The process of applying the offset panel technique to non-developable patterns for this project is the same as that outlined in [Tolman 17].

3 Approach

The first step in designing a foldable fairing was to determine the space that a deployed and stowed fairing could occupy on the front of a locomotive. For a deployed fairing, the space shown in Figure 4 could be occupied without interfering with the view of the engineer, the headlights, plow, or other frontal features. For the stowed position the fairing could occupy the space shown in Figure 5 without interfering with the walkway between locomotives or the coupling mechanisms between locomotives.

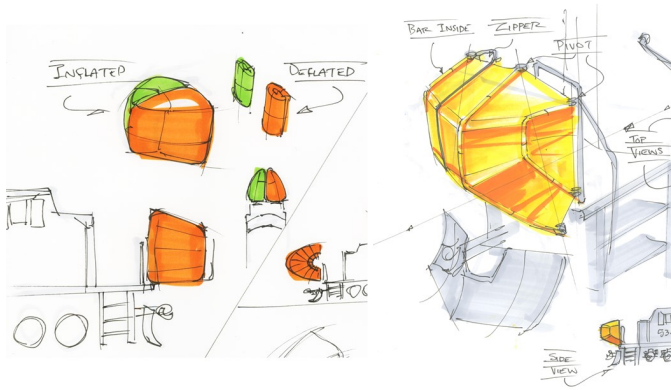


Figure 6: *Fabric-based design concepts. Left: inflatable fairing concept sketch. Right: tension-fabric-based fairing concept.*

In addition to the spatial requirements of the fairing, operational considerations such as the difficulty and time required to deploy and stow the fairing had to be taken into account. The reliability and maintenance requirements were also considered.

The approach taken to design the fairing involved iteration in the following process: Concept Generation, Concept Evaluation, Concept Selection, Design Optimization, and Design Validation. These are described next.

4 Concept Generation

With the functional requirements of the fairing in mind, concepts for reconfigurable designs were generated. Many concept fairings were generated, such as those illustrated in Figures 1 and 6. Although origami was the initial source of inspiration for the foldable fairing project, concepts were not limited to origami-related ideas. In total over 40 different concepts were generated.

5 Concept Evaluation

All of the concepts generated could achieve the desired deployed and stowed shapes so the large number of initial concepts was narrowed down by evaluating them for robustness, cost, ease of use, and maintenance requirements. The number of concepts was narrowed to two: a rigid panel fairing and a tension fabric fairing. To select between the two main categories, the concepts were explored in more depth through evaluation of prototypes.

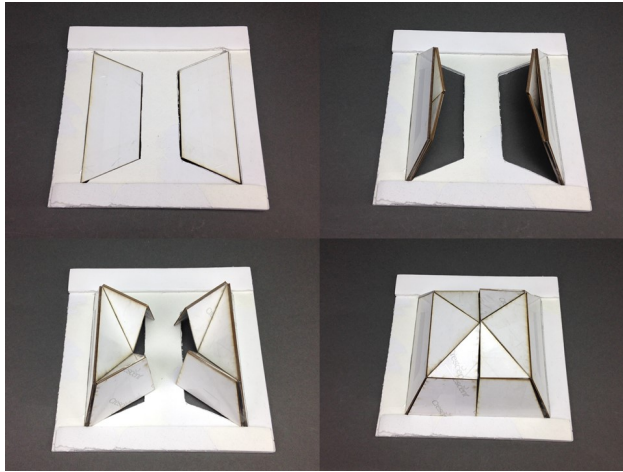


Figure 7: *Proof-of-concept prototype of the non-developable origami-based flat-panel design.*

5.1 Flat-panel-based concept

A flat-panel-based concept was created that utilized two foldable halves. This concept, as shown in Figure 7, folds into two flat panel stacks with a space between the panel stacks that would leave the deck-to-deck walkway between locomotives open.

The pattern of the flat-panel-based concept was designed to approximate the shape of a bullet with flat panels. Because a bullet is a non-developable shape, the origami pattern created to approximate it was also non-developable. This is uncharacteristic of origami which is usually folded from a flat sheet (a developable surface).

Each half of the rigid-panel-based folding fairing is comprised of degree-4 vertices. The prototype shown in Figure 7 utilizes two degree-4 vertices in each half. For each half of the fairing to be able to fold flat, every vertex must be flat foldable.

5.2 Fabric-based concept

The fabric-based concept is based on a fabric membrane stretched across a folding frame. The concept is inspired by many collapsible fabric-based structures such as tents and awnings. The requirements of a nose fairing however are very different from that of many fabric-based deployables. Tents and awnings usually deform easily in strong winds. A fabric-based fairing however would need to maintain its shape in strong headwinds to provide consistent aerodynamic performance.

A fabric-based design is shown in Figure 8. The design utilizes two folding frame members for each half and an architectural fabric that is stretched across the frame. The fabric and folding frame members are attached to a rigid frame. The two halves are secured by means of a zipper that joins the fabric.



Figure 8: Scaled prototype of tension-fabric concept.

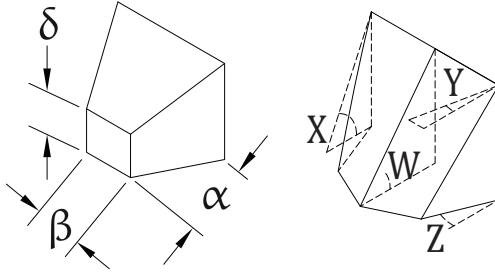


Figure 9: Parameters used in the first study (left) and the second study (right).

6 Concept Selection

After evaluating both the rigid-panel and tension-fabric designs, the rigid-panel-based fairing was chosen for further development for a number of reasons. First, the rigid-panel fairing was evaluated to be more robust against colliding objects. Second, the ability of a rigid-panel fairing to maintain its shape under heavy wind loads was much greater than a fabric-based fairing. Third, a simpler geometry simplified the optimization process to reduce drag.

7 Optimization for Aerodynamic Performance

To determine an optimal geometry for a nose fairing within the design volume, an optimization study was conducted [Stucki and Maynes 17]. Fairing geometries were evaluated using computational fluid dynamic (CFD) software STAR-CCM+, based on the K-epsilon turbulence model at a steady state 80 KPH fluid flow. Over 140 different nose fairings were evaluated and a multidimensional polynomial regression was used to determine optimal geometries.

This study was conducted in two parts. The first study evaluated a parametric nose fairing design where fairing length (α), tip width (β), and tip height (δ) as illustrated in Figure 9, were varied within a constraint space. The results are shown in Figure 10. The resulting optimal design is shown in Figure 11A.

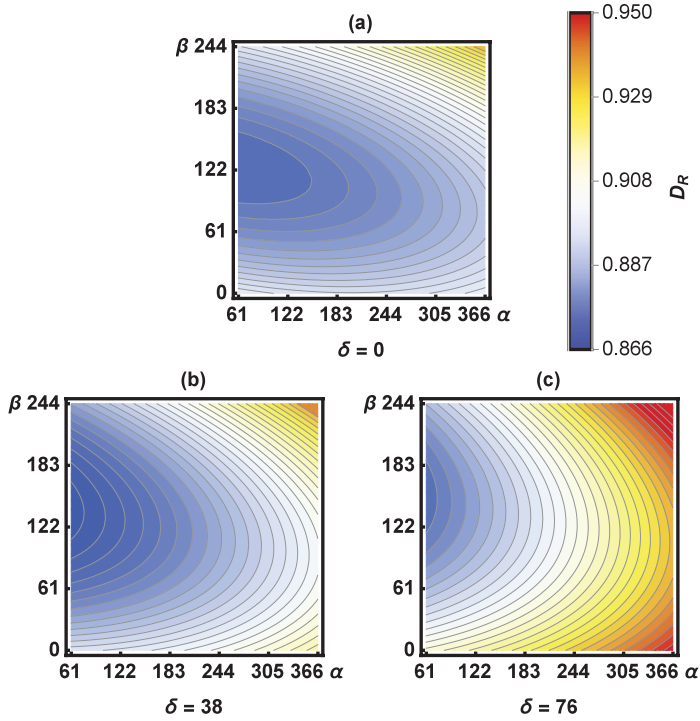


Figure 10: Ratio of locomotive drag with fairing to baseline locomotive drag (D_R) for different geometries of the first study. Fairing length (α), tip width (β), and tip height (δ) are given in units of cm. [Stucki and Maynes 17]

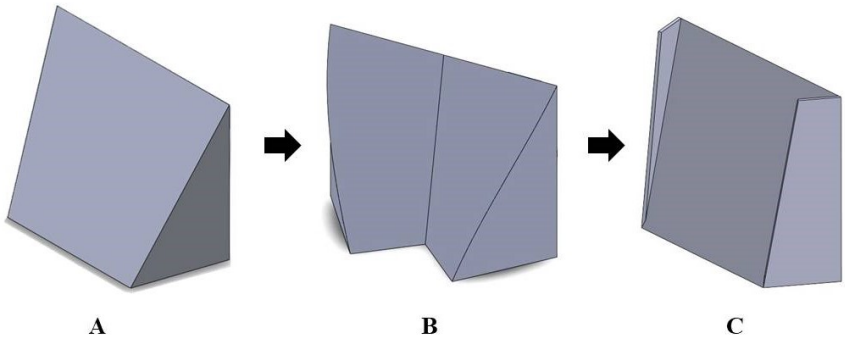


Figure 11: Evolution of the fairing design throughout the optimization process. **A:** Optimized shape of the first CFD study. **B:** Optimized shape of the second CFD study. **C:** Simplified shape that gives performance similar to the curved shape of the second study.

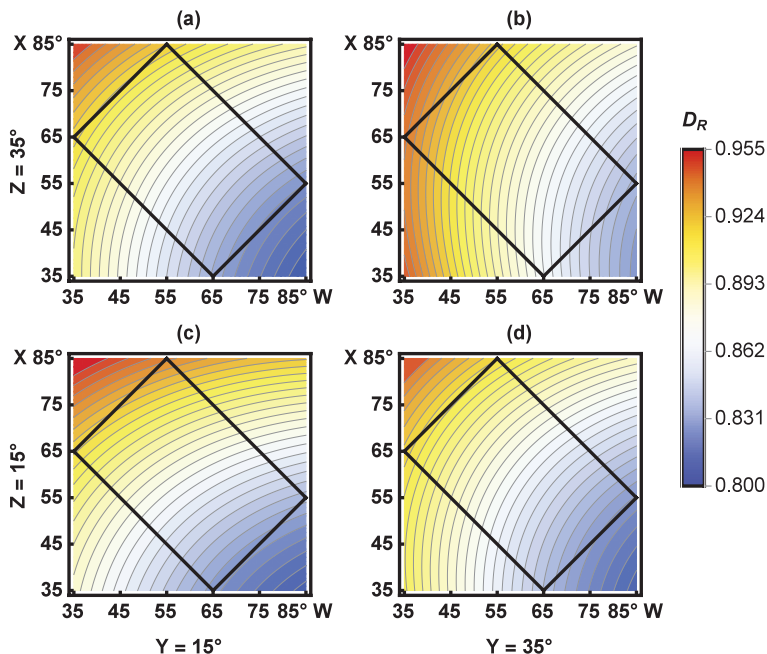


Figure 12: Drag performance of the fairing of the second study given in a drag ratio (D_R) of a locomotive modified with the fairing to an un-modified locomotive. Inside top angle (W), outside top angle (X), top plane side angle (Y), and bottom plane side angle (Z) are given in units of degrees. The box placed on each plot represents the limit constraints of the study. [Stucki and Maynes 17]

The resulting geometry of the first study was significantly different than the starting geometry. The front face of the optimal design had a slope of 70 degrees, much steeper than anticipated. This fairing geometry reduced drag on the locomotive by approximately 15 percent.

The second study used the optimized shape of the first study as the starting point and then varied four angles: the inside top angle, outside top angle, top-plane side angle, and the bottom-plane side angle. Results of this study are shown in Figure 12. The resulting optimal design is shown in Figure 11B. This design reduced drag on the locomotive by approximately 17 percent.

The geometry of the second study is similar to the first study in size and trailing edge angles, but the front face is concave rather than flat. The counter-intuitive concave geometry suggests that directing more flow onto the top of the locomotive helps reduce drag more than directing flow to the sides. When examining the sides and top of the locomotive, the sides tend to have more features that would create drag (e.g. hand-rail supports, vents, wheel assemblies). The fluid flow around a locomotive is complex and a counter-intuitive fairing shape can reduce flow separation and consequently overall drag. Following these studies, wind tun-

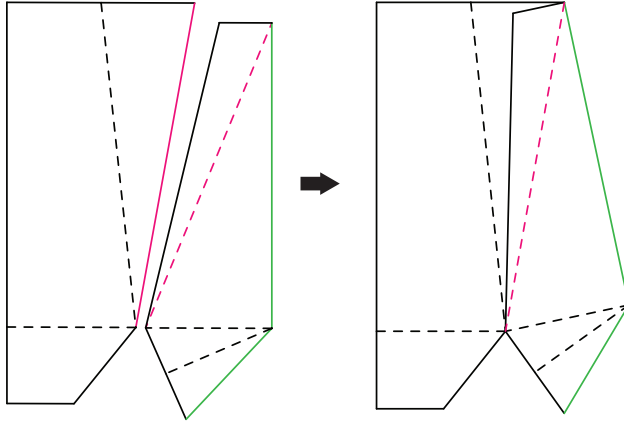


Figure 13: Fold pattern of the non-developable fairing design. Red lines indicate where the face panel attaches to the side panel. Green lines indicate where the panels attach to the frame.

nel tests were also performed to validate the CFD models. The results of the wind tunnel tests showed the same drag reduction trends as the CFD model and overall drag reduction values were the same.

Because the shape of the second study is a curved surface and the goal was to have a flat-panel fairing, the curved shape was approximated with flat panels. Based on the hypothesis that channeling fluid flow over the top of the locomotive achieves higher performance, flat panel designs with similar shapes were explored including the design shown in Figure 11C. This design was created by taking the geometry of the first study and adding vanes to each side to help channel the flow over the top of the locomotive. CFD analysis showed that this flat-panel design reduced drag by over 16%. Although not as high as the 17% drag reduction for the curved shape, the trade-off in stowability and manufacturability was deemed acceptable and the simplified geometry with vanes was chosen for the final design.

8 Final Fairing Design

The fairing shape shown in Figure 11C was selected and the non-developable folding pattern to fold the fairing into the allotted space (see Figure 5) was developed, as shown in Figure 13. Because it is a non-developable surface, the pattern cannot be folded in a single piece of paper. It starts out as two pieces which are then attached along the diagonal of the other piece to form the vane. The green lines in Figure 13 are attached to a static frame which is attached to the locomotive. The frame and the right-hand group of three panels seen in Figure 13 form a degree-4 origami vertex (a spherical mechanism). The other panels of the fairing form an open-loop non-spherical spatial linkage (not an origami vertex) once the hinge axes are shifted to accommodate for thickness. Because the pattern is rigid foldable and



Figure 14: *Eighth-scale prototype constructed from sheet metal.*

revolute hinges that do not store strain energy are used at the fold lines the fairing must use latches and stops to achieve stability in the desired stowed and deployed states.

An eighth-scale prototype as shown in Figure 14, was constructed as a proof of concept of the folding motion and thickness-accommodation methods. 0.85 mm sheet metal was used as the panel material and steel piano hinges were used at the fold lines. The prototype was assembled using spot welds. Offsets in the panels were created by spot welding additional strips of sheet metal between the panels and hinges so that the correct offset distance was achieved. Magnets were used in this eighth-scale prototype to secure the panels in either the deployed or stowed positions, where latches would be used in the full-scale design.

The eighth-scale prototype shares many of the same design aspects as the full-scale design but there are some differences, such as the panel material choice. Although solid steel panels worked well for the eighth scale prototype, for the full-scale prototype this would be prohibitively heavy for the operator who must manually deploy and stow the fairing. A high-strength steel and high density polyethylene foam (HDPE) sandwich panel was selected as the material for the production version of the fairing. This material keeps the weight of the fairing within an acceptable range for one person operation without compromising stiffness or strength. The material is also economical when compared to aluminum sandwich panel options.



Figure 15: Full-scale prototype on a freight locomotive shown in both the stowed configuration (right) and deployed configuration (left). Photo has been modified to remove locomotive identity.

9 Design Validation through Full-Scale Prototype

To validate the operational aspects of the folding fairing, a full-scale prototype was constructed. The prototype, as shown in Figure 15, was constructed with plywood and piano hinges. Latching hardware was used to secure the fairing in the open and closed positions. The prototype was installed on an operational locomotive. Figure 16 provides a perspective of the size compared to a 159-cm-tall person. When deployed, the fairing is 2.35 meters wide, 1.9 meters tall from the top of the train deck, and is 1.7 meters off the ground. The functionality of the foldable fairing design was validated by demonstrating that it could be deployed and stowed by one person in under 30 seconds. The fairing also did not interfere with the features or functionality of the locomotive.

10 Conclusion

The design of an origami-inspired deployable locomotive fairing has been presented. The fairing design is based on non-developable thick origami. Considerations for the design of non-developable thick origami mechanisms have been discussed and we have shown that the offset-panel technique can be used to accommodate thickness in non-developable patterns. The geometry of the fairing was optimized using CFD analysis and multi-dimensional polynomial regression. The resulting fairing design is estimated to reduce drag by over 16% for a locomotive cruising at 80 kph. The design was verified with wind tunnel testing of scaled



Figure 16: *The top of the fairing is 3.6 meters above the ground. An 159 cm tall person provides a visual indication of the fairing size. Photo has been modified to remove locomotive identity.*

prototypes. The deploy-stow functions were demonstrated on a full-scale prototype attached to a freight locomotive. The fairing can be deployed and stowed by one person in under 30 seconds and does not interfere with any of the features or functionality of the locomotive. Using statistics of freight hauling trains, it is estimated that railroads can save over 24,000 liters of diesel annually per train retrofitted with the fairing. For class 1 railroads that have hundreds of trains operating at any given moment, this translates into a fuel savings of 2,400,000 liters annually per 100 trains.

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References

- [Bowen et al. 13] L. A. Bowen, C. L. Grames, S. P. Magleby, L. L. Howell, and R. J. Lang. “A Classification of Action Origami as Systems of Spherical Mechanisms.” *Journal of Mechanical Design* 135:11 (2013), 111008.
- [Chen et al. 15] Yan Chen, Rui Peng, and Zhong You. “Origami of thick panels.” *Science* 349:6246 (2015), 396–400.
- [Delimont et al. 15] I. L. Delimont, S. P. Magleby, and L. L. Howell. “A Family of Dual-Segment Compliant Joints Suitable for Use as Surrogate Folds.” *Journal of Mechanical Design* 137:9 (2015), 092302.
- [Demaine and ORourke 07] Erik D Demaine and Joseph ORourke. *Geometric folding algorithms*. Cambridge university press Cambridge, 2007.
- [Edmondson et al. 16] B. J. Edmondson, R. J. Lang, M. R. Morgan, S. P. Magleby, and L. L. Howell. “Thick Rigidly Foldable Structures Realized by an Offset Panel Technique.” In *Origami⁶*, edited by Koryo Miura, Toshikazu Kawasaki, Tomohiro Tachi, Ryuhei Uehara, Robert J. Lang, and Patsy Wang-Iverson, pp. 149–161. American Mathematical Society, 2016.
- [Filipov et al. 16] E. T. Filipov, G. H. Paulino, and T. Tachi. “Origami tubes with reconfigurable polygonal cross-sections.” *Proc. R. Soc. A* 472:2185 (2016), 20150607.
- [Francis et al. 13] KC Francis, JE Blanch, SP Magleby, and LL Howell. “Origami-like creases in sheet materials for compliant mechanism design.” *Mechanical Sciences* 4:2 (2013), 371–380.
- [Ku and Demaine 16] Jason S Ku and Erik D Demaine. “Folding Flat Crease Patterns with Thick Materials.” *Journal of Mechanisms and Robotics* 8:3 (2016), 031003.
- [Lang et al. 17] Robert J Lang, Todd Nelson, Spencer Magleby, and Larry Howell. “Thick Rigidly Foldable Origami Mechanisms Based on Synchronized Offset Rolling Contact Elements.” *Journal of Mechanisms and Robotics* 9:2 (2017), 021013.
- [Lang et al. 18] R. J. Lang, K. A. Tolman, E. B. Crampton, S. P. Magleby, and L. L. Howell. “A Review of Thickness-Accommodation Techniques in Origami-Inspired Engineering.” *Applied Mechanics Reviews* In Press:TBD.
- [Lukaszewicz 07] Piotr Lukaszewicz. “Running resistance-results and analysis of full-scale tests with passenger and freight trains in Sweden.” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 221:2 (2007), 183–193.
- [McCarthy and Soh 10] J Michael McCarthy and Gim Song Soh. *Geometric Design of Linkages*, 11. New York: Springer, 2010.
- [Miura and Natori 85] Koryo Miura and Michihiro Natori. “2-D Array Experiment on board a space flyer unit.” *Space Solar Power Review* 5 (1985), 345–356.
- [Morgan et al. 16] Michael R Morgan, Robert J Lang, Spencer P Magleby, and Larry L Howell. “Towards developing product applications of thick origami using the offset panel technique.” *Mechanical Sciences* 7:1 (2016), 69.

- [Overvelde et al. 17] Johannes TB Overvelde, James C Weaver, Chuck Hoberman, and Katia Bertoldi. “Rational design of reconfigurable prismatic architected materials.” *Nature* 541:7637 (2017), 347–352.
- [Pehrson et al. 16] N. A. Pehrson, S. P. Magleby, R. J. Lang, and L. L. Howell. “Introduction of monolithic origami with thick-sheet materials.” In *Proceedings of the IASS Annual Symposium 2016 “Spatial Structures in the 21st Century”*, edited by K. Kawaguchi, M. Ohsaki, and T. Takeuchi. Tokyo, Japan, 2016.
- [Stucki and Maynes 17] C. L. Stucki and R. D. Maynes. “Aerodynamic Design of a Locomotive Fairing.” In *Proceedings of the 2nd Thermal and Fluid Engineering Conference, TFEC2017, TFEC-IWHT2017-17708*. Las Vegas NV, 2017.
- [Tachi 11] Tomohiro Tachi. “Rigid-foldable thick origami.” In *Origami*⁵, pp. 253–264. CRC Press, 2011.
- [Tolman 17] Kyler Austin Tolman. “Developing Hybrid Thickness-Accommodation Techniques for New Origami-Inspired Engineered Systems.” Master’s thesis, Brigham Young University, 2017.
- [Xie et al. 15] Ruikang Xie, Yan Chen, and Joseph M Gattas. “Parametrisation and application of cube and eggbox-type folded geometries.” *International Journal of Space Structures* 30:2 (2015), 99–110.
- [You and Kuribayashi 09] Zhong You and Kaori Kuribayashi. “Expandable Tubes with Negative Poisson’s Ratio and their Applications in Medicine.” In *Origami*⁴, edited by Robert J. Lang, pp. 117–128. A K Peters, 2009.
- [Zirbel et al. 13] Shannon A Zirbel, Mary E Wilson, Spencer P Magleby, and Larry L Howell. “An origami-inspired self-deployable array.” In *ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, pp. SMASIS2013–3296. American Society of Mechanical Engineers, 2013. doi:10.1115/SMASIS2013-3296.