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VEHICLE CONCEPTS FOR THE PHOTOGRAMMETRIC INSPECTION OF HYDROELECTRIC TUNNELS

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Abstract: Photogrammetric inspections of hydroelectric infrastructure can provide a significant improvement to the understanding and potential prediction of defect and deterioration trends over time. Hydroelectric tunnel environments pose a unique set of challenges and constraints for performing these inspections and particularly to the required collection of images. This introduces the demand for an assistive system to aid in positioning the cameras in the required positions, which is often inaccessible or impractical to do manually. We have explored a collection of camera positioning vehicle concepts that complete the image collection process within a tunnel while reducing the required time and manual effort. Details on the constraints and criteria for the conceptualization of these designs, as well as the parameters for evaluation of potential performance and applicability are documented. A thorough comparison of these concepts leads to the conclusion of a design concept best suited to complete the inspection in a safe and efficient manner. Expanded details of this design demonstrate the systems ability to adapt to varying diameter tunnels while maintaining a stable and transportable design.

Keywords: Inspection; Photogrammetry; Hydroelectric Infrastructure; 3D Modelling; Robotic Systems

1 BACKGROUND

1.1 Introduction

Tunnels are a significant portion of hydroelectric infrastructure being incorporated as penstocks, intake tunnels or various other tunnels for diverting flow throughout the process. Generating stations typically have a collection of these, often having multiple penstocks and an associated tunnel.

Regular inspections and maintenance are a crucial part of sustaining the life of hydroelectric infrastructure. Accurate inspection provides a better understanding of the infrastructure condition and deterioration trends. This allows owners to better plan maintenance and rehabilitation, to reduce the duration of shutdowns, to extend the period between shutdowns, and to thereby reduce overall infrastructure spending and increase service life. Tunnels are typically shut down for regular inspection and maintenance every few years. During these shutdowns the tunnels are drained, and the production of electricity is halted; if unplanned, this comes at a significant expense as replacement electricity must be purchased throughout the duration of the shutdown.

These tunnels can vary significantly in both length and diameter; often ranging between a couple meters to ten meters or more in diameter and hundreds of meters to kilometers in length. There is also variability in access requirements to the tunnels. Access to these areas can be limited, involving a small porthole and a lengthy path to the entrance point. These paths often involve levels of stairs, ladders, hoists, and various obstacles to avoid while ferrying inspection equipment to the confined space entrance point. The resulting access point can be merely large enough for a person to pass through, often only 0.7 meters in diameter.

Tunnel environments are much different than common outdoor or open environments. They are dark and lack any source of natural lighting; this, combined with a lack of geometric identifying features throughout, poses difficulties visualizing the surface or referencing locations accurately. The surface of the tunnel is typically wet, and silt covered, with potential leaks and sprays spurting from the surface throughout.

1.2 Traditional Inspection Methods

Traditional methods of inspecting tunnels involved the presence of an expert who would personally walk through the tunnel to visually inspect the condition and document any defects or changes in the tunnel. This would often include documentation of observations by size, location (longitudinal and clock location), severity, and inspector comments on deterioration. While this can be a quick process, the information collected is limited to the inspector’s knowledge, experience, and ability to view different areas from the invert of the tunnel. The inaccuracy of defect descriptions able to be collected and the subjectivity of the individual conducting the inspection, compounded by the varying interpretations of those reviewing the collected information can further reduce the quality of the inspection results. This susceptibility to errors and omissions throughout the process indicates the potential for significant improvement of the inspection process.

In summary, limitations identified in the traditional inspection method include difficulties visualizing deterioration and trends from the base of the tunnel, accuracy of the defect descriptions documented, and the subjectivity and potential for human errors in the process (Bradley 2018).

1.3 Photogrammetry and Inspection Quality

The outcome and deliverables from the inspection can be significantly expanded to provide more accurate and extensive information. The creation of high-resolution visual and spatial models is enhancing the traditional inspections of large-scale infrastructure. These models allow for the remote study of the tunnel by an expert without needing to be in the tunnel during the time of the shutdown, as well as a more analytical understanding of deterioration trends over time. This led to the development of a photogrammetric inspection process originally being implemented in the tunnel environments by Bradley (2018) with performance capabilities of millimeter-level visual and spatial accuracy. The data collection process for these models are more intensive than traditional walkthroughs. Lidar can also be used to create these models, however, in many scenarios and environments, photogrammetry has both speed and quality advantages.

The collection of data required for these photogrammetric inspections involves the capture of thousands of overlapping images covering the entire surface of the tunnel. A minimum level of overlap between the images in both directions, radially and longitudinal, about the tunnel is required to effectively create these models. Maintaining a consistent ground sampling distance and therefore a constant distance between the camera and surface, in conjunction with the overlap requirements, creates a cylindrical grid of image capture locations.

1.4 Advanced Inspection Practices

As tunnels are part of a wide range of infrastructure and used in many applications, the tunnel parameters vary greatly which has led to many unique inspection methods and systems. Stent et al. (2015) developed a monorail-based image capture system utilizing a rotating arm which moved along the rail to collect images. The tunnel-specific fixed rail system limits the applicability and adaptability of such a system. For use in free flow tunnels, Hosotani and Yamamoto (2020) attempted to use a self-propelled cart to collect images throughout, but the resulting quality was limited by the rough ground terrain in the tunnel. Additional systems have been implemented for various tunnels and applications (Wang et al. 2019, Nießner et al. 2013, Oleynikova et al.), however the adaptability or resulting resolution are commonly insufficient for a complete and effective inspection.

Bradley Engineering (Bradley 2022) performed the image collection process for photogrammetric inspection in two different tunnels in New Brunswick, Canada: a 7.5 m diameter, 822 m long tunnel in Grand Falls (Bradley 2018), and multiple 8.8 m diameter, 65 m long penstocks in Mactaquac (Bradley, Waugh, Hanscom 2019). Collection of images in these tunnels required rotating the camera around the center axis of the tunnel at a constant offset form the surface, with elevation of the camera reaching upwards of 7-8 m at the peak of the rotation. To effectively reach these positions, an assistive rig was developed to help maneuver the camera about the required circular path; this rig will herein be referred to as TIA, or Tunnel Inspection Assistant (See Figure 1). TIA consisted of a mobile triangular base of aluminum structural members with three wheels, one of which being steerable at the point of the triangle. From this base, an A-frame structure elevated and supported a motor-driven rotating counter-balanced arm with flashes and a camera on one end. The capture process involved incrementally moving TIA along the tunnel a couple meters at a time and pausing to complete an incremental rotation about a plane perpendicular to the tunnel axis. After a brief delay to allow for settling of the arm, multiple images were captured during each rotation to obtain the required overlap (Bradley, Waugh, Hanscom 2018).

Figure 1: Model of original TIA design used to inspect Grand Falls tunnel (Bradley 2018)

Some limitations and opportunities for improvement in this design and process have been identified throughout it’s use. While effective in performing the fundamental inspection, TIA was a tunnel-specific design, meaning a different version had to be designed and constructed for each tunnel to account for different diameters. This greatly limits the applicability of this type of rig for the image collection process. Transporting TIA into the tunnel requires the assistance of the generating station workers as it’s large components and framework are not able to fit through the normal access point. The manual efforts required to transport and maneuver TIA within the tunnel, along with the incremental approach of the rotation and travel limit the speed that can be achieved.

2 CRITERION AND CONSIDERATIONS

The design conceptualization process involves developing a concrete understanding of the fundamental requirements of the camera positioning system. In this case, this refers primarily to the system’s ability to collect the required images to perform the inspection. In detail, this includes:

- Maneuvering the camera throughout the cylindrical grid of image capture locations.
    - The two-dimensional planar circular path around the tunnel axis and the rotation required to remain perpendicular to the surface.
    - Maneuvering along the tunnel length.
    - The orientation control of the camera.

- Transportation into the tunnel through a 0.7-meter porthole and be ferried through any path to the access location.
- Maneuvering the photography equipment safely and stably, while avoiding blur caused by shaking and instabilities.
- Practically of fabrication in a reasonable timeframe and budget.

Expanding on the fundamentals to consider factors that would make a more optimal design will be the differentiating element of the design selection process. Some factors that extend beyond the fundamental application of the system include:

- The level and ease of adaptability:
    - While each concept can have the fundamental ability to adapt to different tunnel diameters, a concept that can do so with ease, or has more extensive control over its position makes a more attractive solution.
- The simplicity of assembly/disassembly in the tunnel:
    - As the system is likely to be disassembled for transportation and access into the tunnel, being able to assemble the system within the tunnel with limited tools and in a reasonable time is important to the optimization of the inspection time.
- Weight
    - Weight of the total assembly and individual component/subassembly weight impacts the manual efforts for transportation.
- Ease of manufacturing:
    - A system that can be fabricated in a local environment with limited use of specialized equipment or technicians simplifies the process.
- The accessibility and availability of the required equipment, products, and materials:
    - Easily obtainable products and equipment can be crucial for the fabrication process as lead times can often be a limiting factor in a project’s timeline. This also applies in the event of a product’s malfunction and need for replacement parts.
- The complexity of control and operation, including hardware and software aspects:
    - The control scheme can be complicated by redundancies in the control of the degrees of freedom. Need for synchronization of equipment can also increase control complexity and introduce the need for higher precision equipment.

3 CONCEPTS

Some key aspects that are considered in all concepts that provide the foundation for capture or are common improvements over the TIA functionality include the ability to vary the elevation of the arm, adjust the rotating arm length to accommodate different tunnel diameters, incorporate control over the camera orientation, utilize a driven and steerable base, and include a second set of photography equipment to increase efficiency. The methods of achieving these elements vary throughout each design, the following section details some of the concepts that have been considered throughout the process.

3.1 Cantilever Concept

The first design concept was derived as an expansion of the TIA, the original image collection system, that would incorporate an extensive amount of additional adaptability that the TIA did not have. A rotational arm with cameras cantilevered off each end to provide the rotation and frontal offset required for capture remains the primary element, while a linearly actuated adjustment of the arms length provides the camera radius adaptability. Elevating this arm from a vertical mast, as opposed to a rigid frame, provides the adaptability for reaching the center of different tunnels, as well as providing easier access to the camera equipment. One actuation for each degree of freedom, along with the decoupled relationship between the elevation and rotation of the arm creates an uncomplicated method for providing the motions required. Figure 2 below details this concept.

This simplistic concept comes with a noticeably front heavy and frail skeleton causing concerns of overall stability. Specifically, the frontal cantilevered load the cameras apply to the arm suggests a need for heavy duty arm framework to counter the torsional impact. This adds to the already concerning overbearing forward moment created by the general configuration.

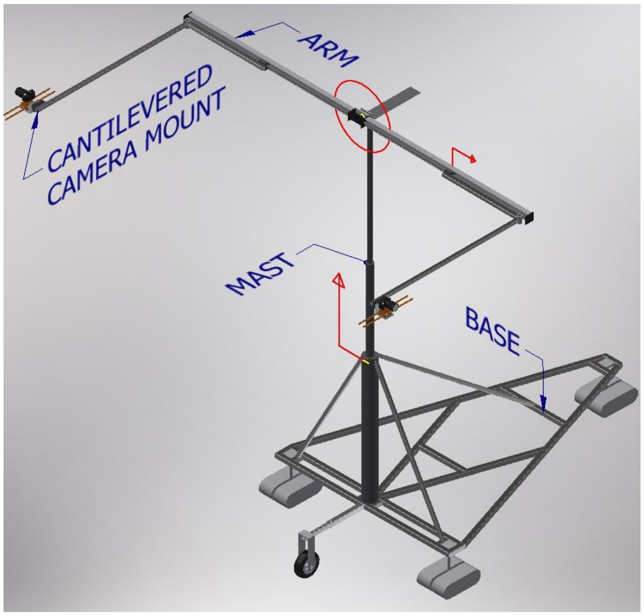

Figure 2: Model of Cantilever concept design

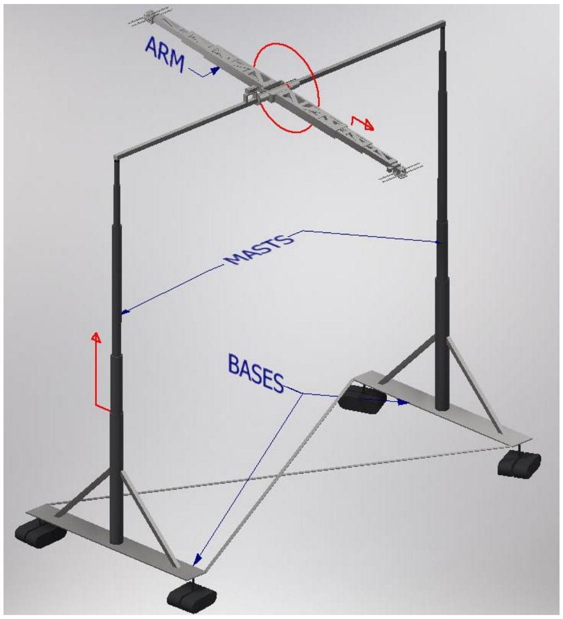

Figure 3: Model of Double Mast concept design

3.2 Double-Mast Concept

With the idea of balance and stability in mind, an alternative mast design was conceptualized utilizing two synchronized vertical masts to provide the elevating action required, see Figure 3 for a visual of this concept. A crossmember linking the two masts lengthwise along the tunnel, and a rotational bidirectional arm attached to the center of this crossmember which holds the set of cameras at a variable offset from the tunnel axis. Centering the arm between two masts counters the frontal moment concern that was presented in the Cantilever concept. The symmetrical design also allows for identical operation in either direction with similar base frames on either end. Operation in a curved tunnel poses a concern for stability and contortion as significant alignment is required for the separated yet synchronized masts and quad-wheel base. Misaligning the base ends about the curved surface, which can occur if either of the base ends shift to a different clock location about the tunnel than the other, could invoke twisting of the crossmember and be a detriment to the stability of the system.

3.3 Stewart Platform Concept

Following the symmetrical concept, a more three-dimensional balanced system influenced by the concept of the common Stewart mechanism (Bingul, Karahan 2012) has been considered. This concept has improved articulation with the four independent limbs, creating six degrees of freedom in the end effector platform. Two variations of this concept are considered; one with cameras mounted directly to the end effector platform having the articulation of the limbs to follow the circular camera path. This allows for a relatively small load at the top platform but requires a significantly greater reach both vertically and horizontally. This leads to a very wide base and limb lengths that are not practical.

Alternatively, the inclusion of a variable length arm like the previous concept that extends from the platform with the limbs sole purpose to center the platform within the tunnel. Figure 4 below shows a model of this concept version. This reduces the required length of the limbs and ensures the platform remains centered, balancing the load. The additional degrees of freedom between the platform and the cameras presents a level of redundancy and precision in camera positioning that is likely to create unnecessary complexities in control. Structurally, the additional load of the arm creates a strong concern for the required strength of the actuated limbs, even at the shortened length compared to the first variation. As well, actuators with these capabilities are likely to be dimensionally large, heavy, expensive, or not feasible at all.

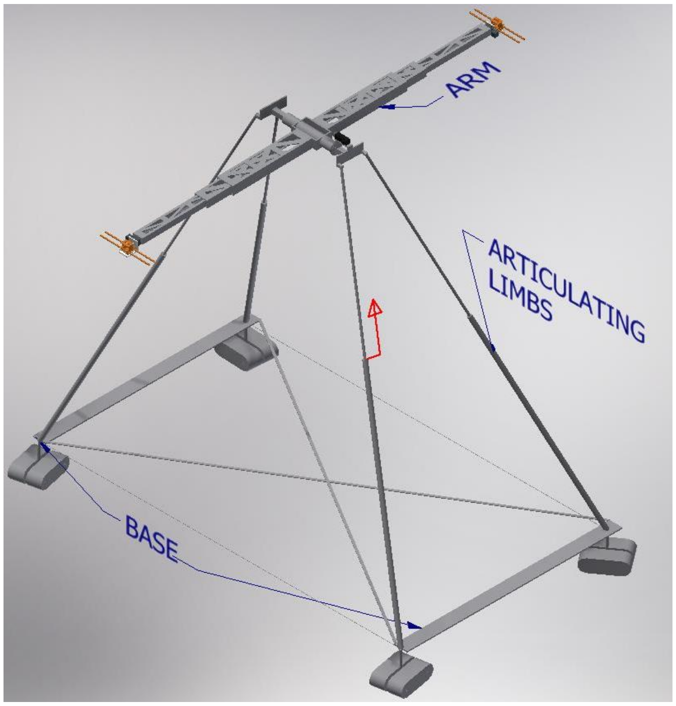

Figure 4: Model of Stewart Platform concept design

3.4 Boom Truck Concept

This concept took influence from telehandlers of the construction industry and bin pilers from the farm industry. These systems work on the premise of a telescopic set of extension booms that pivot and extend from a mobile base. The angle and extension of the boom provide the elevation and forward offset of the camera, removing the need for a cantilevered arm such as in the cantilever concept. The attached variable length arm at the tip of the boom independently provides the rotation and image capture operations. As the angle of the boom relative to the tunnel changes to account for different tunnel diameters, the arm must pivot about the boom tip to remain in a plane perpendicular to the tunnel axis. Figure 5 below details each of these components. With the boom elements originating at the rear of the base, an increase in stability can be obtained as compared to the Cantilever concept with a pure frontal load. This concept also decouples the image capture rotation with the elevation and offset set by the tunnel parameters. Although multiple actuations are required, variability of the frontal offset is achieved in addition to the elevation and camera rotation radius, which is not achieved by the previous concepts. Initial concerns of this system are the overall weight, size of the system components, and therefore stability caused by the potentially large components.

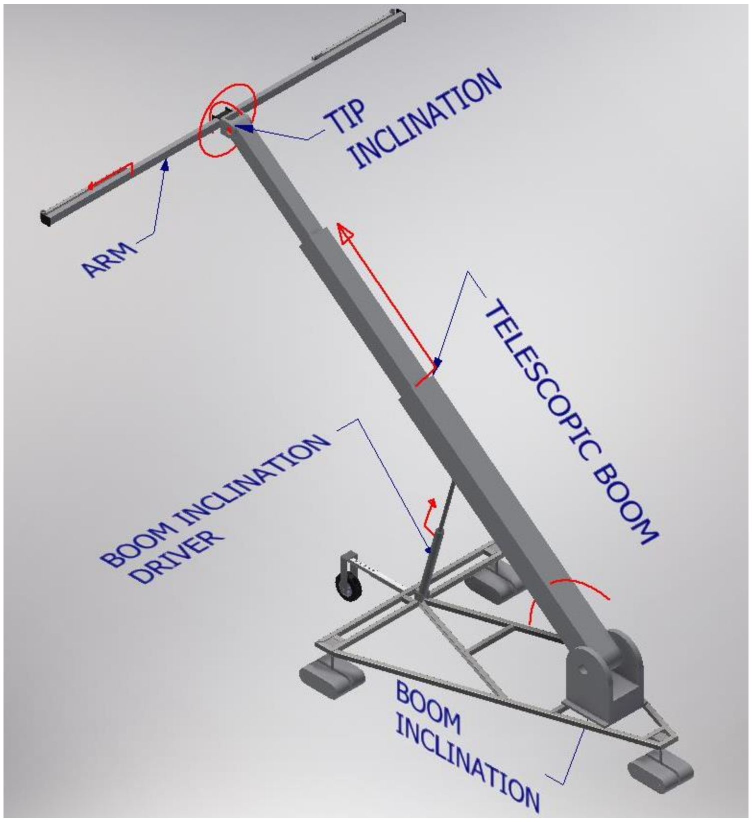

Figure 5: Model of Boom Truck concept design

4 EVALUATION AND DECISION

4.1 Evaluation

After detailing and understanding the functionality and abilities of each of the proposed concepts, comparisons were made based on the general functionality, the outlined considerations and aspects that influence an optimized design. For explanation purposes, these have been ranked based on their foundational performance, as well as the more niche factors. The summarization of this ranking can be seen in Table 1. Beyond the analytical comparison, personal experience and preference were also influential factors in the consideration of the designs. The comfort level, familiarity, and personal inclination that a concept presents affected decisions as well.

Table 1: Evaluation Table

Concept	Adaptability	Ease of Assembly	Overall Weight	Ease of Manufacturing	Control Complexity	Ease of Procurement	Total
Cantilever	4	2	1	1	1	2	11
Double Mast	3	3	3	2	3	2	16
Stewart	2	4	4	4	4	4	22
Boom	1	1	2	3	2	1	10

*Ranking from 1-4 relative to each other, 1 being the best rank.

4.2 Decision Rationale

Carefully maneuvering multiple sets of high-quality camera equipment through a cylindrical tunnel places a significant emphasis on reliability and stability, while the unique parameters that are applied by various tunnel diameters requires a significant level of adaptability to effectively perform image data collection. These factors put the Boom Truck option at the forefront of the selection process. It has a more supported structure that is well balanced over the base compared to the Cantilever option, as well as additional variability in adjusting the forward distance between the cameras and the base. It also has a solid triangular base that has greater reliability on the cylindrical surface when compared to the multi-section base as in the Double Mast and Stewart platform concepts. Although this concept may have more structural components, the simplistic, common-shaped members are conceivably able to be broken down into modular components that make transportation easy.

The chosen concept will herein be referred to as the ATI, for Automatic Tunnel Inspector. The following section will document the further detailed design throughout continued revisions, including potential structural components and configurations.

5 DESIGN DETAILS

Providing the foundation for the ATI is a triangular base constructed of aluminum HSS members; the smaller internal triangles, along with the rectangular front section and bordering members allow for the disassembly for easy transportation and fitment through the tunnel porthole. This base sits above three independently driven and steered wheels at each corner of the triangle. The independent control of each wheel allows for complete maneuverability in any environment; pure translation, pure rotation, or a combination of the two.

Extending and inclining from the rear of this base is a two-stage telescopic rectangular boom; extension is provided by a linear actuation within the boom, while the inclination is driven through a linear actuator between the front of the base and the boom. The combination of these two actuations provides the elevation and frontal offset positioning of the arm. In conjunction with the arm positioning, a linear actuated pivoting tip (like the boom inclination) at the end of the boom maintains the arms rotation axis alignment with the tunnel axis. The combination of these three actuations and the resulting affect of the arm position can be represented as a planar system for kinematically describing the arms position and angle relative to the base. This position would typically remain constant for any tunnel of constant diameter that is to be captured with similar image properties. These can also be changed during image capture to permit capturing variable diameter tunnels.

With the arms position set, the arms radial length can be adjusted to meet the required camera radius through a linear actuated extension of each arm end. At the end of these arms, the photography equipment (camera, flashes, batteries) is mounted on a single-axis rotary stage for control over the camera's orientation (portrait or landscape). The final actuation is a driven rotation of the arm and equipment from the tip platform on the boom. This acts in a plane perpendicular to, and about, the tunnel axis. This set of actuations provides complete control over the cameras position and orientation, efficiently meeting the requirements for an effective image collection process within a cylindrical tunnel. The combination of joints and frames between the base and cameras can be described as a complex serial manipulator extending from the fully mobile base.

Figure 6: Detailed conceptual design of ATI beside a 183cm tall person.

Figure 6 above provides a visual of a more detailed revision of the chosen ATI design. Further analysis of this design concept including preliminary kinematic and dynamic simulations, exploration of steering concepts, controls theory and implementation have been documented by Keizer et al. (2022).

6 CONCLUSION

The implementation of photogrammetric inspections can provide personnel with a significant improvement to the understanding of a tunnel’s deterioration trends and enhance maintenance practices. A functional and efficient system for collecting images is critical for conducting an inspection in a timeframe that fits within the typical tunnel shutdown period while reducing manual efforts required.

Throughout this paper, four unique design concepts have been explored and compared to determine an optimal concept for capturing images within a cylindrical tunnel. A cantilever concept was considered for its minimalistic design and simplicity in control and operation, however strong stability was a detrimental concern. A symmetrical double mast alternative countered the balance concern however sacrificed reliability due to the alignment consistency required in a cylindrical tunnel. A Stewart platform-based concept provides substantial maneuverability improvements at the expense of control complexity and specialized equipment requirements. The selected Boom Truck concept presents a structurally well-balanced design with sufficient adaptability and portability while maintaining a reasonable level of simplicity in control and operation through its decoupled design.

The study of the design conceptualization and selection process has led to the further design and development of the ATI with the goal of future implementation of the inspection system in an actual tunnel environment. The development of this image collection system involving the rotating arm and circular camera path leads to many potential variations of image capture sequencing and maneuvers to optimize the collection process. The process can be further optimized by a deeper understanding of the image density that is produced by varying of image overlap. This system provides a foundation for future optimization and automation of the inspection process.

7 ACKNOWLEDGEMENTS

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