A TRIANGULATION BASED PROFILER.

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ABSTRACT.

This paper reports a triangulation based measuring system which has applicability to the increasing demand for close range measurement data. This system uses a linear sensor array and diode laser light source and is discussed with respect to theory, calibration and practical results. An analysis of the use of this profiler to acquire spatial information (e.g. wriggle surveys, refurbishment) and local information (e.g. deformation) is given. Consideration is given to: errors from setting up, establishing a datum, profile position, and the inherent errors particular to triangulation systems.

1. GENERAL INTRODUCTION.

The rapid measurement of structures and cavities is the aim of many recent systems[1,2]. However, the more successful are limited to: the diode laser or light emitting diode using 'time of flight' or heterodyne methods, optical triangulation or acoustic methods. Ideally measurement would be performed with a narrow collimated beam directed to a small unique point on a given surface. However until a fast coaxial laser range finder is produced with data acquisition speeds in MHz then there will continue to be a call for alternative methods and techniques to measure distances with speed and accuracy. One such method is based on optical triangulation using linear sensors[3], this particular method has benefits which can be realised with current technology having data recording rates of kHz and reasonable resolution with sub-pixel accuracy.

Optical triangulation with linear sensors has been widely used to determine distances in industrial metrology[4] (range 200mm, high accuracy) and robotics[5] (range 10m, low accuracy). However this technique has not received the same attention for close range applications in surveying and industrial measurement where a range of 0-10 metres and medium accuracy might be required.

The structures and cavities encountered in civil engineering, and the large work pieces produced in mechanical engineering present a growing demand for specialist measurement techniques. The subjects vary in size from a few tens of millimetres to a few tens of metres, often demanding sub-millimetre accuracy with a high data recording and processing rate. In practise, for many applications there are no robust general purpose systems available. Optical triangulation systems have an excellent reputation[6] for being quick, robust, reliable, and accurate in operation, the obvious limitations being occlusion and non-linearity. This paper presents a partial solution to both of these problems and attempts to analyse the causes of its errors and reports on the results obtained from research on the accuracy of these techniques.

2. ENGINEERING SURVEYS.

Surveying in the engineering environment is often required to determine the shape of a surface, the coordinates of unique points on a structure to ascertain correct construction, or monitor the structure over a period of time to determine possible movement and/or change of shape. Usually the surveying investigation is required to be carried out quickly with an equally rapid analysis of the data.

(i) Surveys required for this type of work have usually involved observations being taken from a network of well established and coordinated instrument positions to clearly defined points of detail, e.g. corners of stone, bricks, window frames etc., or easily visible targets fixed to the fabric of the structure. Such observations have been made with tapes, levels, theodolites and electromagnetic distance measuring devices. In many instances because of the time involved on site to gather the data, only a limited number of points may be observed, consequently surface shapes are obtained by interpolation while construction control and movement detection is limited to a few, well chosen, points often restricted in value by sighting and identification demands.

(ii) Photogrammetry has been used in the quest for rapid data collection, as the method requires only a short time on site and affords measurement of almost any point recorded in the photography. However the resulting photography requires processing and analysis on expensive instrumentation, with little reduction in the control survey work.

A variant of traditional photogrammetry has been examined at City University for some time, in which, the features of interest are illuminated with a plane of light, and the resulting line of light on the surface photographed and subsequently coordinated. The coordinated data are obtained in the office for points along each line. Fig. 1(a) shows a typical profile plotted from one such set of coordinates out of over seventy recorded in a tunnel system. Fig. 1(b) shows a plan view of the profiles of the three tunnels in their correct spatial position.

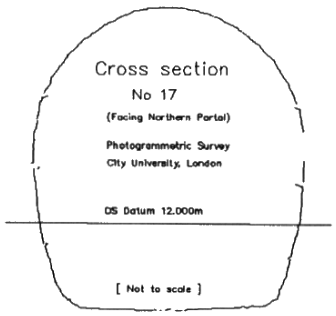

Fig. 1(a). Cross section of rail tunnel.

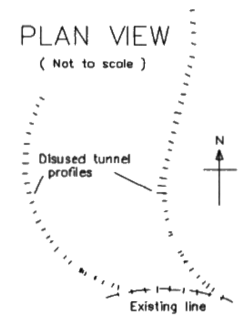

Fig. 1(b). Plan view of all cross sections.

The plan position of each profile is obtained by observing at least two points on each profile using observations of angle and distance from survey instruments fixed in position from a suitable control network. Such limited observations can be performed simultaneously with the photography and hence will not unduly extend the site occupation.

Optical triangulation when used in a suitable configuration is able to gather data of a similar nature to the previous photography based system. However, it will perform more directly, accurately and rapidly than alternative methods, with the results being presented fully analysed, if necessary, on site. The number of points recorded will depend on the nature of the surface under examination, smooth newly installed concrete to soot-caked broken brick linings or sludge covered rock in a mine-shaft.

It is of interest to compare the performance of each system. If the problem is to, say, measure 5000 points on a grossly irregular surface at a range of 1-4m, see Table 1, obviously the number of points required will depend on the nature of the surface since interpolation will give a distorted representation of a surface if insufficient data are obtained.

Method	Data acquisition time	Post processing	Accuracy
Electronic tacheometry	33 mins •	No	≈ 3mm
Stereo photography	15 sec	Yes	≈ 3mm
Light line + mono Photography	15 sec	Yes	≈ 2mm
Optical triangulation	5 sec	No	≈ 1mm

• O.4 sec per measurement

Table 1. Comparison of measurement times for four techniques.

It would appear from the estimated times in Table 1 that :

(i) Electronic tacheometry, when in the tracking mode will collect small quantities of information very quickly, but is unsuitable for small structures and artifacts at close range.

(ii) Photogrammetry:

(a) Stereo - this system gathers a lot of data very quickly on site, the quality is good and there is the added advantage that the negative, stored in archive, may be measured as often as required. However the films have to be processed and the analysis is time consuming, especially for a lot of data, in addition good quality control is required in each stereo pair. A useful advantage of this system is that the pairs of photographs can be viewed stereoscopically for detailed examination of the subject.

(b) Mono - this system is as fast on site as stereo, it: requires processing and analysis, which is a little faster than for stereo, provides a good archive, and is less demanding on control.

(iii) Optical triangulation, is able to compete favourably in this situation being mid-way between photogrammetry, with regard to speed of measurement, and is better than electronic tacheometry in terms of accuracy.

An example of data collected by an optical triangulation system is shown in Fig. 2, which is a cross-section of the laboratory at City University.

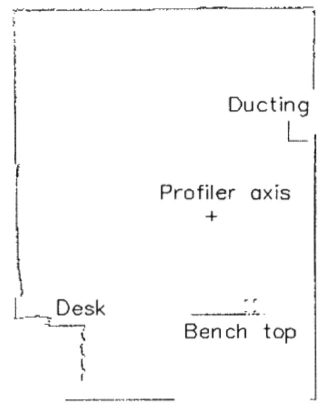

Fig. 2. Cross section of laboratory.

This paper will describe the optical triangulation measuring system, and outline its use in obtaining cross-sections of structures. The errors in measurement will be analysed from the global errors associated with surveying for the cross-section location, the local errors in the cross-section orientation and finally the sources of error with respect to the cross section itself. This data will enable both wriggle type surveys and deformation surveys to be efficiently carried out.

3. OPTICAL TRIANGULATION.

There are a number of possible configurations for optical triangulation systems, but the principle of operation remains the same, that is, a light source identifies a point on a surface to be measured, the reflections of this light will radiate in a variety of directions, a small proportion of which is collected by a lens and focussed on a sensor which provides the means to distinguish the, relatively high intensity peak from the background illumination and record its position. A configuration used at City University for testing is shown in Fig. 3.

(i) Optical triangulation configuration.

(ii) Images of light reflected from surfaces S_1 and S_2.

(iii) Calibration curve showing the relationship between image position and measured distance.

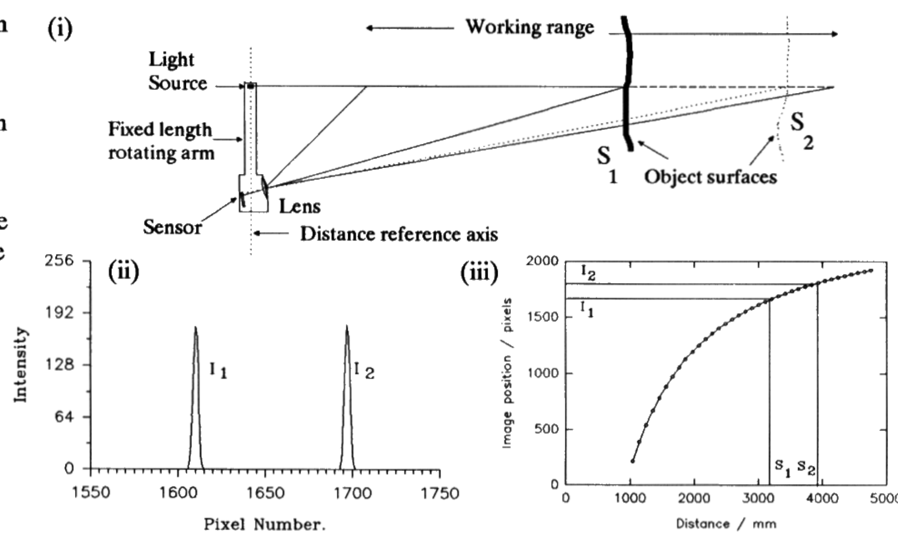

Fig. 3. Optical triangulation configuration.

The system is approximately linear over short ranges but measurement over longer ranges will be non-linear. Occasionally a triangulation system will be used as a null finding device with no calibration and interpolation where the linearity is not of great importance.

The prototype developed at City University progressed through a number of configurations to its present form[7]. It is able to gather 2D, and 3D, spatial information about structures such as road, rail and tube tunnels, mine-shafts and sewers etc. as shown in Fig. 4. To collect data appertaining to a cross section of a structure, the measuring arm is rotated about the distance measuring axis, thereby describing a cross-section as the light source is perpendicular to the measuring axis. Further measurements, at new positions of the measuring axis, will result in the spatial coordinates of cross-sections of a given structure in 3D space.

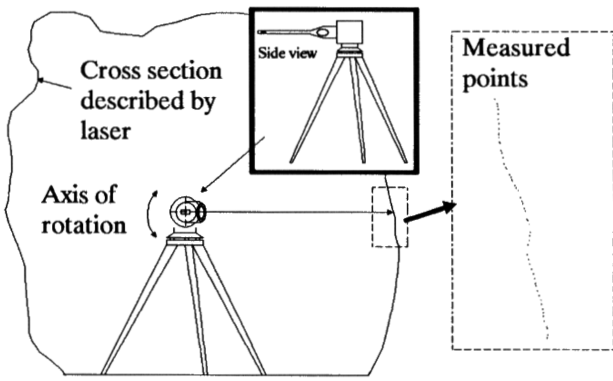

Fig. 4. Prototype configuration and operation.

4. MEASUREMENT ERRORS.

All measuring systems are subject to error, it is necessary to identify the possible sources of these errors and assess their magnitude and likely consequences when attempting to determine the efficacy of the system. To avoid the temptation to exaggerate the accuracy of the subject of this paper, the various errors, where identified, have been analysed both empirically and theoretically.

4.1. SURVEY ERRORS.

4.1.1. Errors is profile location.

The rotating laser profile measuring device is portable and can be arranged to indicate and measure a profile at almost any attitude and orientation. Thus, the profiler can measure the internal profile of a tunnel or ship-hull or the external shape of a building or clay model of a car. The positions of the profiles may be fitted to appropriate pre-marks, alternatively the position of the laser line may be marked on the subject. In both cases, marks on a tunnel wall, ship side, building face or clay surface will need to be surveyed to fix their position relative to a national or local control system.

Often tunnel profiles are required as part of a structural surveillance programme so that repeated measurement of the same profiles is necessary. In this situation, it is essential that the profile can be guaranteed to be vertical and that the pre-marks are identified in the resultant measured profile. Thus providing good survey practice is maintained the coordinates of the pre-marks may be determined to a wide range of accuracies. The survey operation can involve a traverse through the tunnels to fix the control stations from which observations to the pre-marks can be made, hence their coordinates determined. Providing the starting point of the laser rotation is known i.e. horizontal in a vertical plane, the derived coordinates for all the profile points will be to the same coordinate system. Thus the errors in location of the profiles will be those normally associated with control surveys. See Fig. 5(a).

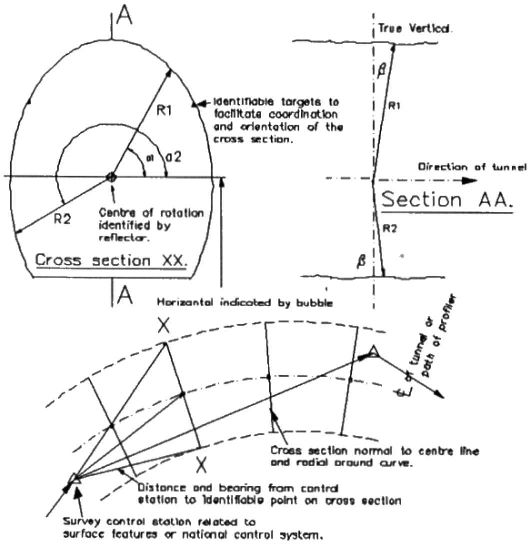

Fig. 5(a). Survey errors.

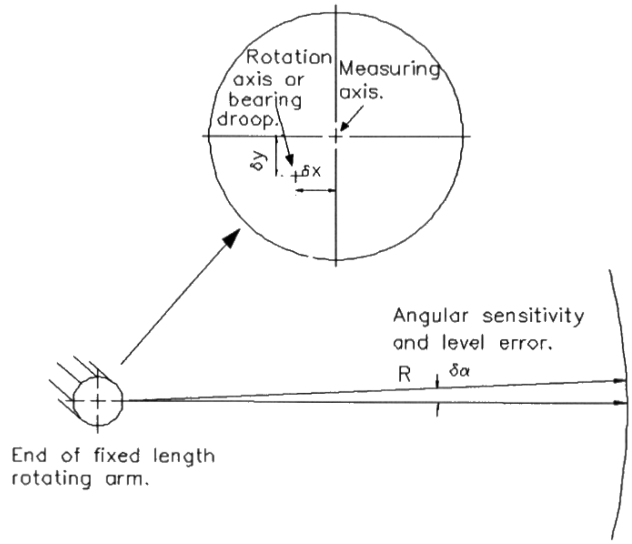

Fig. 5(b). Mechanical errors.

4.1.2. Errors in profile acquisition.

The laser profiler consists of a fixed laser source sending a beam normal to the axis of rotation of the measuring arm, from which the beam impinges on the surface of inspection. Thus for creditable results the laser source must be correctly fitted to the axis of rotation, so that, the beam traces out a plane and not the surface of a cone with a conic section for the profile, see Section AA in Fig. 5(a). When the plane is vertical, it is not important to have the profiler on the axis of the tunnel in spite of variations in the radius of the rotating laser beam. When the beam is not perpendicular to the axis, which in turn must be horizontal, the profile will be an irregular conic section, making it impossible to determine the correct surface coordinates.

4.2. MECHANICAL ERRORS.

4.2.1. Angular measuring errors.

(i) Rotation about the horizontal axis. The starting point is determined by a spirit bubble of known sensitivity, say, 10" per graduation, leading to a error of $dx = R*\mathrm{Sin}(\delta\alpha)$, $dy = R*\mathrm{Sin}(\delta\alpha)$ where R is the radius from the central measurement position (R will vary point to point), see Fig. 5(b).

(ii) Angular rotation errors. The laser and camera measuring system is rotated to collect measurements from a central axis, the angle can be determined in a number of ways, a stepper motor gives a constant angular rotation per step or an optical encoder can be read directly at the position of measurement. Both methods will introduce an angular error which will give a false position of the distance measurement. In some circumstances this is not important, for example, if a circular tunnel is being monitored for deformation from a central measurement position, this error will be slight, however if a boundary location is required, this error is significant. This error is given by $dx = R*\mathrm{Sin}(\delta\alpha)$ and $dy = R*\mathrm{Sin}(\delta\alpha)$, see Fig. 5(b).

(iii) Bearing errors. To provide complete cross-sections the measuring arm must be cantilevered and rotated. This allows the possibility of errors caused by the bearings being less than perfect because of wear or lack of fit. The bearings would be designed to minimise this error but it must be a part of the error analysis.

4.2.2. Eccentricity.

The axis of rotation and the axis of measurement may not be coaxial leading to a systematic eccentricity error. This error can be written as $\delta x, \delta y$. See Fig. 5(b).

4.3. MEASURING ERRORS.

It is apparent from the geometry of an optical triangulation scheme, see Fig. 3, Fig. 6(a) and Fig. 6(b), that the sensor resolution and chosen measurement range will define the accuracy of measurement. This accuracy will be inversely proportional to the range of measurement, however, the desired range may be obtained with a number of differing configuration parameters which affect the accuracy or range of measurement. Hence for a given accuracy, sensor or range of measurement, the remaining parameters must be carefully chosen to minimise the gross error in distance measurement. There are further errors which are beyond the designers control but which must also be identified and understood before a full theoretical analysis of distance measurement errors is completed.

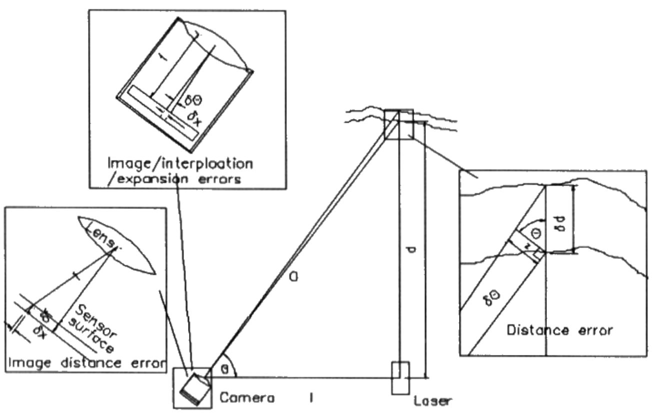

Fig. 6(a). Camera errors.

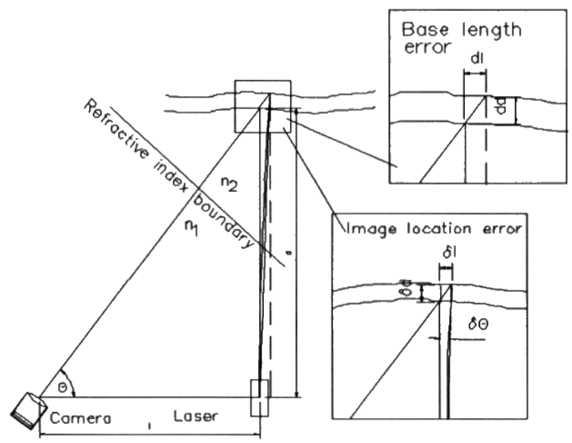

Fig. 6(b). External errors.

(i) Triangulation base length changes with temperature. The components, light source and camera, are held in a fixed orientation with respect to each other, see Fig. 6(b), and the measurement axis. This configuration is maintained mechanically thus, there is always the possibility of change from the calibration state due to temperature or stress, a major source of error will be in changes to the triangulation base line. The temperature range over which the system may operate could be as much as 20°C. The thermal expansion properties of materials are well known so two solutions are possible, first, to use a material of low thermal expansivity such as invar, or second to enter corrections to the calibration for the ambient temperature. The prototype developed at City University uses aluminium components for ease of manufacture, strength and lightness, and the majority of testing was done in the laboratory where the temperature was controlled.

(ii) Sensor position changes with temperature. Change of position and expansion of optical components with temperature also causes errors. The sensor, which is mounted on a Printed Circuit Board (P.C.B.), is held in the camera/lens housing and will move with temperature. The expansion coefficient will be that of silicon, as the sensor is constructed on a silicon substrate and the chip package is designed to expand at the same rate, so that unwanted stresses are not allowed to build up. The ambient temperature range over which the sensor is likely to operate is 0°C to 30°C, however since the chip itself will warm up during use, it may not reflect atmospheric temperature.

(iii) Change in image distance with temperature. The last error due to temperature change is that of the camera lens system expanding or contracting, this affects the focus on axis, but, off axis will alter the position of the image with respect to the sensor chip and hence introduce an error due to the changed configuration.

(iv) Laser pointing stability. The operation of the triangulation scheme depends critically on the light source providing a well collimated beam to illuminate a measurement position on the object, and upon the pointing stability of the source.

The pointing stability of lasers sources is good with variations of less than 0.1mrad, but over longer distances needs to be accounted for in the error analysis.

(v) Ambient temperature, pressure and humidity. The laser beam and the reflected light all pass through the medium, air, before entering the camera, thus it is possible for the light to encounter temperature, pressure or humidity gradients which can affect the direct path of the light to the camera, giving an error. Large temperatures differences can exist e.g deep gold mines in South Africa have rock temperatures as high as 63°C[8].

(vi) Surface irregularities. Image location errors can cause distance measuring errors if the surface to be measured has sharp discontinuities either in form or contrast, is aligned at unfavourable angles or is outside the optimum range of reflectivity required by the sensing system.

(vii) Location of image with respect to sensor. The precision with which the the Gaussian laser spot can be identified with respect to the sensor determines one of the fundamental limitations to the resolution of the system as a whole. This precision will depend in the size, number and distribution of the pixel sites and upon the sub-pixel interpolation algorithms. The size of the pixels sites on the prototype are 13μm square, with 2048 pixel sites, the sub-pixel accuracy improvement for cooperative surfaces extends from 1:1 to 100:1. The size of sensors currently availiable have a maximum of 6000 pixels.

(viii) Interpolation errors from calibration data. To use the system for distance measurement, data is collected from the image location algorithms and related to distance from the measuring system axis by means of an interferometer or other high accuracy measuring system. If there are 'n' pixels and a sub-pixel interpolation of 'x' then there are n*x possible calibration points which can be measured. However as 'n' is typically 2000 and 'x' may be greater than 5, then there may be a very large number of measured points to be collected. It is preferable to either characterise the data by a function such a polynomial or to interpolate with a reduced number of points. Both of these methods will cause an error if the model of the system characteristic does not perfectly match the true data.

SUMMARY.

The eight errors described from i...viii, can be sub-divided into random and systematic errors, the random errors are best treated statistically and are unavoidable, the systematic errors can be estimated and corrections made. The error types are shown in Table 2, and are those estimated for the prototype configuration.

	Error type		Distance error ranges / mm		
Error type	Random	Systematic	Min distance	Camera axis	Max distance
a		✓		0.284	
b		✓	0.03		1.9
c		✓	0.18		10.96
d	✓			0.192	
e	✓			0.0043	
f	✓			0.17	
g	✓			0.172	
h	✓			0.017	

Table 2. Summary of errors.

The standard deviation of a random variable is the positive root of the square root of the sum of squares of the random errors[9], using the values computed above, the standard deviation is 0.31mm. This can be compared to the actual standard deviations obtained experimentally.

To design an optical triangulation measuring system with minimum errors over a given range, the variable parameters require careful consideration as several configurations are possible. For a comprehensive analysis of a given design a computer simulation of the results is desirable where errors can be assessed and "trade offs" made between the competing parameters. A Computer Aided Design system has been developed to model various configurations to assess non-linearity, range and dimension, work is continuing to refine this software to handle errors in the modelling.

5.0. RESULTS.

The practical testing of the prototype was carried out on an optical bench with an interferometer integrated into a computer controlled calibration and interpolation system. A number of tests were carried out with several hundred measurements per test. The interferometer provided the means of assessing the error in each measurement and standard deviations for the data were computed. Fig. 7, is a distribution plot of standard deviations obtained. The prototype uses a 2048 pixel CCD sensor, 750 nm solid state laser source, and has a 0.7m fixed length measuring arm.

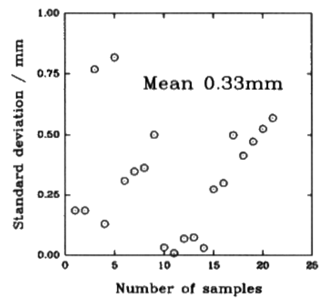

Fig. 7. Standard deviation error distribution.

6.0. CONCLUSION.

The application of an optical triangulation measuring system to surveying situations has been analysed with respect to the errors introduced through surveying, mechanical errors and distance measuring errors. The analysis concentrates on surveying of complete cross-sections, but the technique is not restricted to this application, indeed may be better suited to specific manufacturing uses. This technique has potential to acquire spatial data faster and more accurately than some existing techniques allow. Further work is required to improve the understanding of the theoretical errors. In addition investigation is still necessary into the effects of environmental conditions on refraction errors and collimation integrity.

7.0. ACKNOWLEDGMENTS.

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