Determining Structural Rock Mass Parameters Using a Computer Vision System

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Field mapping on exposed rock faces comprises the acquisition of visible geometric features and the measurement of several parameters, such as joint orientations, trace lengths, joint bridges, or values for spacing, as well as areal information on e.g. lithological regions, altogether aiming at getting a proper model of the rock mass, in order to support excavation layout or stability analyses.

Usually, those geometric features are measured using a compass-clinometer device and a tape measure. Although measuring using a compass-clinometer device is convenient and easy to apply in field, certain drawbacks concerning its use can be identified. For example, taking an orientation measurement requires physical contact. If the measuring point cannot be reached safely, the measurement cannot be taken or only at risk. Additionally, the number of measurements taken is rather low due to time and accessibility restrictions. Furthermore, the compass reading itself might be problematic if the joint surface is rough and wavy, as it is not clear which is a representative measuring point. This is especially true for measurements within larger rock faces, as the overview on the whole scene might get lost, when working close to the rock face. This might lead to measurements, which are not representative.

Generally, current field work has several drawbacks, as the collected data might be incomplete (few measurements), incorrect (no metrics), and inconsistent (subjectivity in field mapping). However, further rock mass analyses rely on these data, which motivates for improvements.

Related work

Although there has been a long tradition of analysing images from remote sensing, in order to detect geological structures, only few attempts to employ terrestrial (close range) photographic systems for collecting such data are described. The ongoing development of digital cameras, especially in having more picture elements, and the increase of computer power allows crossing former limits.

Linkwitz (1) used a photo-theodolite and a mechanical stereoscope for measuring the orientation of discontinuities. This allowed to overcome the need for having physical access to get measurements. Rengers (2) applied the same principle to a rock face in a quarry. Both showed the principle to be applicable to measure joint orientations, having the advantages of

- faster data acquisition,
- more reliable analysis over large areas, and
- getting measurements at inaccessible regions.

Bestimmung von Gebirgsstrukturparametern mittels eines Computer Vision Systems

Eine digitale Panoramakamera und Software zur Auswertung der erzeugten Bilder bilden zusammen ein Computer Vision System, das die gegenwärtige Praxis zur Bestimmung von Gebirgsstrukturparametern verbessert. Es werden dabei hochauflösende Bilder von Felsaufschlüssen erzeugt und mittels speziell zugeschnittener Software verarbeitet. Die Software gestattet eine interaktive Analyse geometrischer Strukturen wie Trennflächenabständen oder Ausbisslängen, aber auch die Bestimmung von Flächen und Raumlagen. Die Messungen erfolgen dabei am Computer, das heißt berührungslos, wodurch die Datenerfassung sicherer wird, speziell dann, wenn Messungen in schwierig oder gar gefährlich zu erreichenden Gebieten erfolgen müssen. Bei der Betrachtung kann schnell zwischen Überblick und Detailansicht gewechselt werden, wodruch die Bestimmung der geotechnisch signifikanten Messpositionen erleichtert wird. Darüber hinaus erlauben die Daten die Bestimmung von Rauigkeitsparametern von Klüften oder Oberflächen. Mit dem innovativen System wurden bislang Aufschlüsse von 6 bis 60 m Höhe aufgenommen, wobei das System so flexibel ist, dass dieser Bereich noch ausgedehnt werden kann. Das System wurde an Steinbrüchen und Tunnelbaustellen in Österreich getestet.

A computer vision system, consisting of a digital panoramic camera and software that processes its images improves present practice for determining structural rock mass parameters. High resolution images of exposed rock faces are taken and then analysed using specially tailored software components. The software allows an interactive analysis and yields geometric rock mass parameters, such as distances, areas, or discontinuity orientations. The measurements are taken indirectly on the computer, i.e. without the need for physical contact which makes the field work safer, especially in areas that are difficult or even hazardous to reach. Zooming allows to quickly change the point of view which supports to identify those measuring points that are geotechnically significant. Beyond, roughness parameters of discontinuities or surfaces can be computed from the images. Using the innovative system, rock faces from 6 to 60 m heights were recorded so far, whereas the system is flexible enough to extend this range. The system was tested on quarries and tunnel construction sites in Austria.

Hagan (10) used a pair of conventional single lens reflex cameras and photogrammetric principles for a close range application in a deep underground environment. Franklin et al. (3) applied different image processing algorithms, in order to get an automatic singularisation of pieces from a heap of broken rock. Since the results seemed to be good for certain conditions and poor for others, some used a digitiser board to identify relevant structures interactively, such as Tsoutrelis et al. (4), or Crosta (5).

Orientation measurements from images of a high rock wall were described by Roberts and Poropat (6), who acknowledged again the advantages. However, they used a single lens reflex camera which is limited to a certain field of view depending on the used lens. Using longer focal lengths one gets a higher spatial resolution but a smaller field of view. Shorter focal lengths behave conversely. One way to overcome this contradiction is to use a panoramic camera that rotates the optical system during image acquisition. In Slama (7) an application of this method in aerial photogrammetry has been described. As this is a scanning principle, only unmoved objects can be recorded without showing distortions.

The system presented here uses the same principle, but an electronic sensor. A CCD array is rotated and scans its surrounding (“line-scan” camera). Independent from the used lens and thus from the achieved spatial resolution the field of view can be up to 360°.

As this image geometry needs a special treatment, proprietary software components were established that enable spatial reconstruction and measurements from the images.

A Computer vision approach

Principle

Computer vision can be understood as connecting a computer with (digital) cameras and processing the images in order to obtain information on the recorded scene or objects. Three-dimensional computer vision (3D vision) is inspired by human perception and tries either to reconstruct objects from images or to understand the contents of a scene.

Figure 1 outlines a computer vision approach for geotechnical data collection: A sensor system generates at least two images of the rock face. Due to the high quality of the images concerning spatial resolution and colour depth, they represent an objective and comprehensive documentation of the rock face and its visible structures.

The images are then processed in two ways:

- the recorded surface is automatically reconstructed leading to a three-dimensional surface model and
- an interactive analysis is performed by an operator, who annotates the relevant geological features using software tools, which are tailored for this kind of assessment.

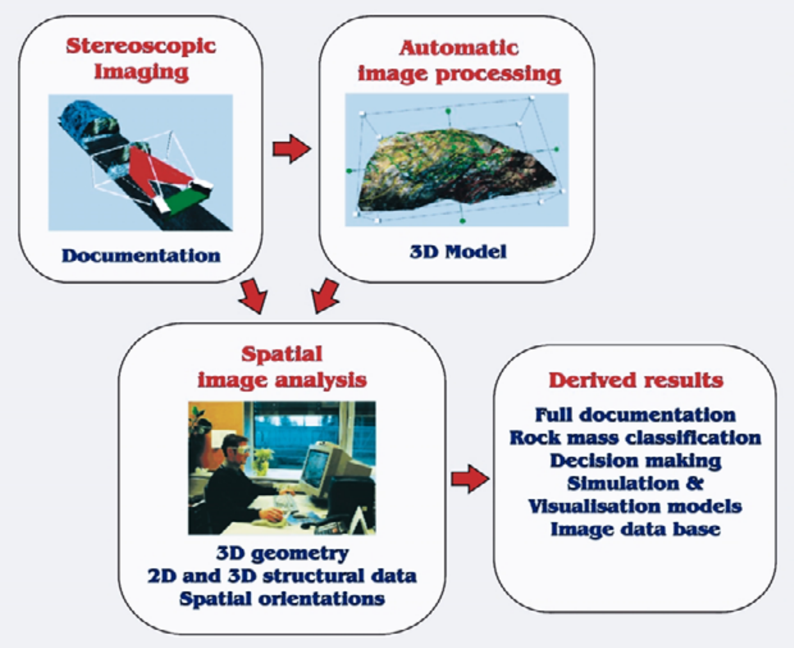


Fig. 1 Computer vision principle: a panoramic camera takes at least two images of the exposed rock face. Software components support the assessment of the images and the derivation of rock mass parameters.

Bild 1 *Das verwendete Computer Vision Prinzip: eine Panoramakamera erzeugt zumindest zwei Bilder des Aufschlusses, Softwarekomponenten unterstützen deren Bewertung und die Bestimmung von Gebirgsparametern.*

The interactive stage delivers structural maps comparable to digitised hand sketches. Combining interactive and automatic analysis results, three-dimensional structural maps are derived. Furthermore, it becomes possible to measure spatial orientations from the reconstructed model.

The panoramic imaging system

The imaging source bases on a digital line-scan camera. It has three CCD arrays, one for each of the colour channels red, green, and blue. The camera is mounted on a tripod and controlled by a notebook computer that instantly stores the acquired image information. The imaging system has its own power supply and weighs less than 10 kilograms, i.e. it can be easily transported by a single person (Figure 2). Due to the flexibility of the system (no external cabling), it can be set up on another standpoint easily.

Typical images taken with this camera have about 90 million picture elements (Megapixels) for a full panorama (confer a currently good standard digital camera has about 6 Megapixels). This means that tunnel faces are recorded showing details of about 2 mm per pixel or slopes of e.g. 50 m height are represented at 10 mm per pixel both enabling the analysis of fine structures.

Fig. 2 The imaging system applied in a subsurface environment.

Bild 2 *Das Aufnahmesystem bei einer Anwendung unter Tage.*

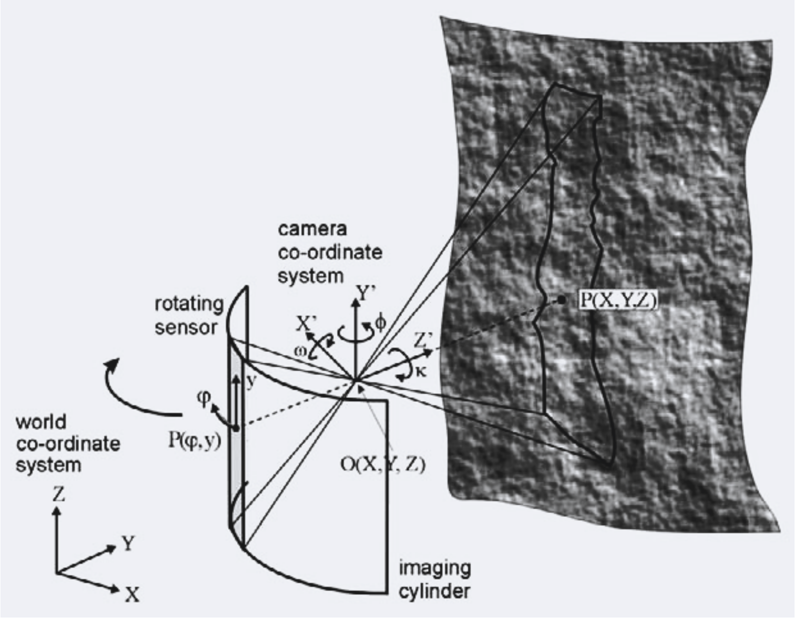


Fig. 3 Sensor model of the panoramic camera.

Bild 3 *Abbildungsgeometrie der Panoramakamera.*

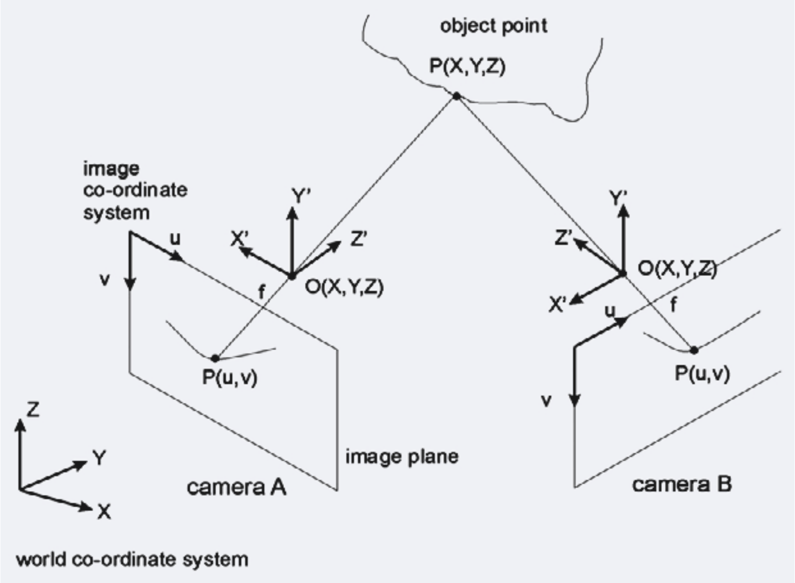
Measurement from images

Before measurements can be derived a sensor model is required, i.e. a mathematical description on how object points are mapped onto the image (interior orientation) and geometric information about where the camera is in relation to the surrounding area (exterior orientation). The special geometry of a line-scan camera differs from the perspective conditions of a single lens reflex camera. Figure 3 shows the basic geometry of a panoramic line-scan camera. Note, that a single image column reflects only a small strip of the surrounding area. To produce a two-dimensional picture, the camera has to be moved. If the movement is a rotation the resulting image does not reside on an image plane but rather on a virtual cylinder (Figure 3).

The cylindrical perspective can be transformed into an image, which one might be familiar from single lens reflex cameras. This image warp procedure yields images that allow the application of standard algorithms to determine the image orientation.

Fig. 4 Point reconstruction from a stereoscopic image pair.

Bild 4 *Prinzip der Punktrekonstruktion aus stereoskopischen Bilddaten.*



The interior orientation of a camera can be determined using a test field containing targets with known co-ordinates. The interior orientation includes the focal length, the geometric distortion of the used lens, and the position of the principal point (7). Once the interior parameters are known, relative measurements become possible.

Relative measurements in camera space

The imaging system itself defines the co-ordinates, i.e. measurements do not relate to the surroundings. However, relative measurements within a single image pair are valid and have metrics up to a scale factor. This configuration requires no additional positioning information which is often sufficient for geotechnical assessments, like stability analyses. As the measurements base on panoramic images, the large field of view benefits for certain object geometries, e.g. when having a rock face that is long compared to its height.

The exterior orientation refers to the location of the centre of projection and the pose of the optical axis within the object co-ordinate system. By observing at least three non co-planar reference points (points with known co-ordinates in the object space) the exterior orientation can be determined uniquely. This process was adapted for panoramic cameras by Case (8) and for digital line-scan cameras by Gaich (9). If the interior and the exterior orientation are known absolute measurements from the images are possible.

Absolute measurements within object space

Structures are measured in relation to a given (external) object co-ordinate system. Reference points must be visible, but they can be at any place around the camera, as the panoramic image and its field of view covers them. The referenced standpoints of the camera lead to the arrangement outlined in Figure 4. The co-ordinate frames O(X,Y,Z) refer to the camera orientations, the points P(u,v) represent corresponding image points and P(X,Y;Z) shows one (reconstructed) point on the rock surface.

Image analysis

Several image processing steps are required to develop a surface model and subsequently extract geotechnical parameters from the acquired data. The following outlines the major activities.

Interactive structural analysis

A single rock mass image from a stereoscopic pair is used to interactively annotate geotechnical relevant structures that are identified within the rock mass. This approach was predominantly used in the past, in order to digitise structural information (in two dimensions) from conventional photographs (4, 5, 10).

The major problem in automatic identification of discontinuities so far, originates from changing rock mass conditions and the task to determine only those structures with a geotechnical relevance or significance. Fully automatic approaches, as described by Franklin et al. (3), Reid and Harrison (11), or Fasching (12) do not deliver satisfactory results at present, especially if an image covers different rock types. Too many parameters in a chain of processing steps influence the final results and have to be considered individually. Thus, current analysis software seem not to be as robust as needed, to be used for different rock mass conditions simultaneously.

With the tools available presently, interactive analyses by a person experienced in rock mass analyses, are required. The software handles the images and allows an annotation of discontinuities by directly "drawing" on the images, i.e. the structures are marked on the screen as graphical overlays. Furthermore, areas of a certain attribute, e.g. lithology, can be marked. The resulting structures are grouped to data sets that can be displayed and assessed selectively, e.g. by computing statistics.

From these data, relative measurements in two dimensions can be derived, i.e. distances like joint bridges or joint spacing are determined in relation to each other. A statistical evaluation of such magnitudes, for instance the distribution of the distance to length ratios yields information on the rock mass beyond the usual practice without additional effort.

Automatic surface reconstruction

Surface reconstruction allows to recover the three-dimensional shape of the rock mass exposure from (at least) a pair of images. Three basic steps within this task can be identified:

- Matching: This is the process of identifying corresponding points within the image pair. This task is an important basis for the quality of the reconstructed surface: the denser and more accurate the point correspondences are detected, the more reliable are measurements derived from the surface model.
- 3D point reconstruction refers to the computation of the three-dimensional object co-ordinates of a surface point based on the corresponding image points and the orientation of the cameras. The result of this step is an unorganised set of 3D points (point cloud). Figure 5 shows the principle.
- Mesh generation ensures a connection between the single points of a point cloud. Often used are triangulated irregular networks (TIN) like the Delaunay Triangulation, which results in a surface description exclusively, composed by triangles.

Results

Structural maps

The resulting structural maps from the interactive analysis can be aligned with the automatically computed surface reconstructions, if both results base on the very same images. With that, two-dimensional structural maps become three-dimensional and therefore enable the derivation of 3D magnitudes of the structures, like the true length of discontinuities or distances between them.

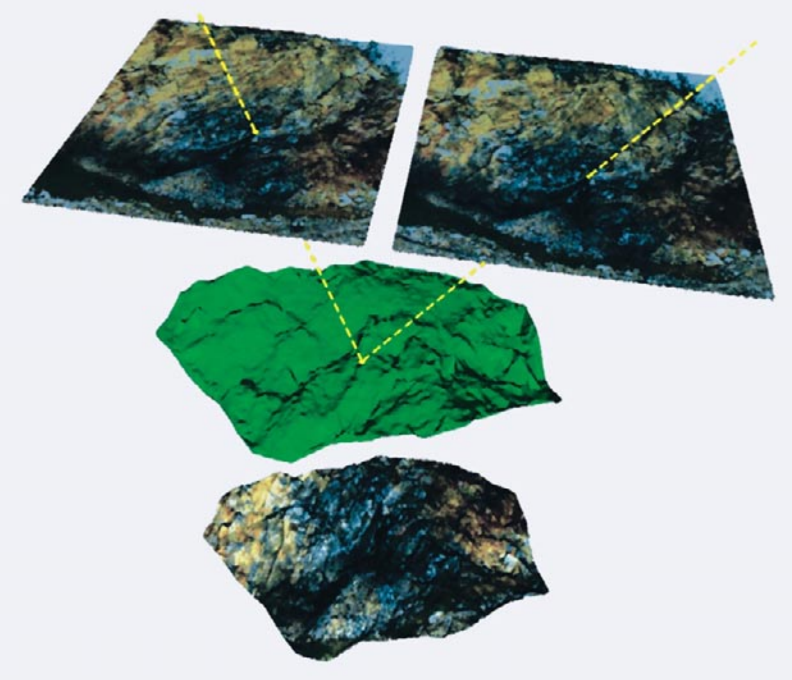


Fig. 5 Surface reconstruction principle. Corresponding points in a stereoscopic image pair lead to a reconstructed point. A bunch of reconstructed points is connected to a surface.

Bild 5 *Prinzip der Oberflächenrekonstruktion. Korrespondierende Punkte eines Stereobildpaars führen zu einem Punkt. Ein Punkthaufen wird zu einer Oberfläche verbunden.*

The data format allows a statistical evaluation of the features, such as histograms (Figure 6) of discontinuity trace lengths or discontinuity spacing. These values can be used for the rock mass characterization.

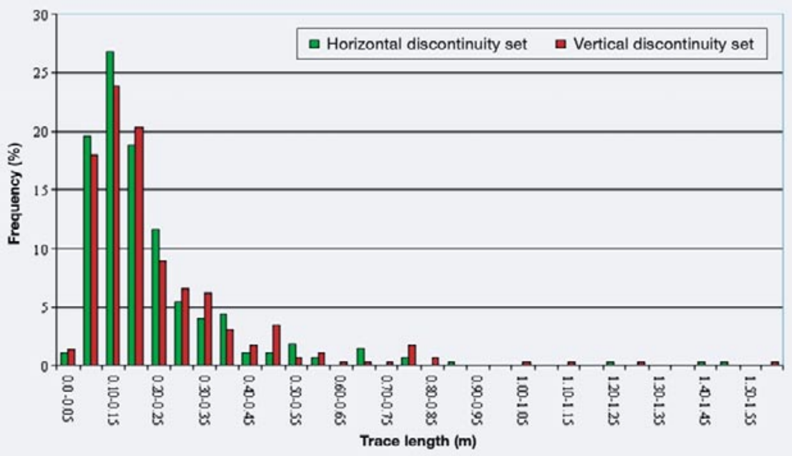
Besides, the rock mass model is available in a standard graphics file format which allows an easy interchange with existing applications in visualisation and modelling, and can be used as input for numerical simulations.

Discontinuity orientations

The measurement of the spatial orientation can be derived from single 3D point measurements. A spatial triangle is determined by three surface points. If the surface points are chosen to lie on a discontinuity then the normal vector to this surface triangle represents the orientation of this discontinuity. This principle was already used in geotech-

Fig. 6 Example for statistical evaluation of discontinuity trace lengths.

Bild 6 *Statistische Auswertung am Beispiel von Trennflächenlängen.*



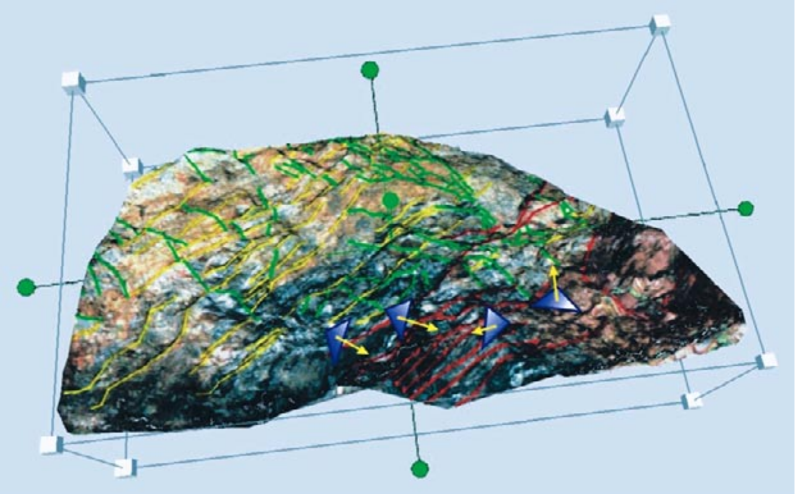


Fig. 7 Orientations are measured by means of small triangles positioned on the reconstructed surface.

***Bild 7** Orientierungen werden mittels kleiner Dreiecke, die an der rekonstruierten Oberfläche positioniert werden, gemessen.*

nical analyses based on conventional photographs, e.g. from Linkwitz (1) or Feng et al. (13).

The pragmatic approach delivers the orientation measurement in relation to the given coordinate system, or, if no external referencing has been used, allows the determination of relative orientation measurements. As the orientation measurements are taken indirectly on the computer, the whole process might be seen as a kind of a virtual compass-clinometre device. An example is shown in Figure 7.

Roughness

As the acquired data show the structures in a digital form and at a good spatial resolution, the data have the potential for analyses currently hardly performed. For example the roughness of the reconstructed surface or the roughness of single traces can be computed. This information is valuable for stability assessments.

Benefits and conclusion

The derivation of geotechnical data from images overcomes certain drawbacks of present practice in collecting structural rock mass parameters and improves the quality of the data. Using a special panoramic camera allows a detailed and comprehensive documentation of a rock surface. Once the camera is calibrated, measurements can be derived from the images.

The images are processed using software components specially tailored for geotechnical analyses. They enable spatial measurements of geometric rock mass structures, such as discontinuity lengths, region sizes, or spatial orientations. The indirect measuring principle does not require physical access to the measuring points, which improves safety. Measurements at a high number do not require additional efforts but just another selection on the computer. The measuring principle can be seen as a kind of virtual compass-clinometre device.

Accessing rock faces from images has the advantage that a quick change of the point of view is possible which means fastly witching between an overview of the rock face and a detailed representation. This is especially helpful in identifying those measuring points that are significant for the rock mass analysis.

Summarising, the computer vision system is a supplement for the current field work of the geologist. It improves the present geotechnical data acquisition process, completed by measurement and analysis possibilities not existing so far and makes the work safer and more efficient for the geologist/geotechnical engineer. The results can serve as input for certain other processes, such as numerical simulations, visualisation or documentation purposes. It allows the computation of rock mass parameters usually not applied, e.g. roughness values.

The method can help to define a new standard for the acquisition of structural rock mass parameters and supports the quick generation of realistic rock mass models instantly available on site.

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