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Bachelorarbeit

Poly-directional Stability of Granular Matter

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Ziel und Aufgabenstellung

Das Ziel der Arbeiten, die im Rahmen der vorliegenden Bachelorarbeit durchzuführen waren, bestand darin, die Existenz des poly-stabilen Zustands statischer Granulate experimentell nachzuweisen. Dazu sollten eine Versuchsanlage geplant und aufgebaut werden und die entsprechenden Messungen ausgeführt werden. Grundlage der Arbeiten war ein vorläufiges, vom Betreuer aufgebautes Experiment, das zu Beginn der Arbeiten nicht funktionsfähig war.

Die Versuchsanordnung besteht aus einem flachen Zylinder von etwa 40 cm Durchmesser, der zur Hälfte mit scharfkantigem Granulat (SiC-Schrot) gefüllt wird, und der sehr langsam um seine horizontal liegende Achse rotiert wird. Im relevanten Drehzahlbereich (typischerweise 0.2...1 Umdrehung pro Minute) stellt sich ein schmaler Fluß des Granulats an der freien Oberfläche des Granulats ein. Das vom Granulat ausgefüllte Gesamtvolumen wächst bis zu einem charakteristischen Wert, worauf es dann schlagartig kollabiert. Die Messung des Volumens mit optischen Verfahren und die Messung und Analyse der statistischen Eigenschaften der Intervallängen zwischen den Kollapsen liefern Aussagen über die Stabilitätseigenschaften des granularen Stoffs und waren Teil der Aufgabe.

Die Bachelorarbeit besteht aus zwei Teilen:

1. Der Bericht über die experimentellen Resultate. Dieser wird in Form des Manuskripts "Poly-directional Stability of Granular Matter" von F. Zimmer, J. E. Kollmer und T. Pöschel geliefert. Das Manuskript wurde zur Veröffentlichung in der Zeitschrift "Physical Review Letters" eingereicht.
2. Einem Anhang, der den Versuchsaufbau, die Methoden der Bildverarbeitung und der statistischen Auswertung im Detail erklärt. Außerdem sind die im Rahmen der Arbeit angefertigten MATLAB-Programme enthalten.

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Poly-directional Stability of Granular Matter

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By means of a rotating drum experiment, we introduce the state of *poly-directional stability* in jammed granular matter where the material responds elastically to small stresses in a wide angular interval. Only to small stresses which are directed in a relatively small interval of directions the material responds by plastic deformations. The state of poly-directional stability complements the *fragile* state, where the material responds elastically to small applied stresses only in a certain direction but even very small stress in any other direction would lead to plastic deformations. Similar to fragile matter, poly-directionally stable matter is created in a dynamic process by self-organization.

PACS numbers: Valid PACS appear here

In most cases, jammed granular matter responds elastically to small applied stresses irrespective of the direction of the applied forces. In some cases, however, the dynamics of certain granular flows may lead to a jammed state which responds elastically only to stress in a certain direction. Even very small stress in any other direction would lead to plastic deformations. This *fragile* state of granular matter has attracted much attention recently. The term *fragile matter* was coined by Cates et al. [1] as a state of solid granular matter which responds elastically only to *compatible* loads, in correspondence to the way of its creation. If loaded in an *incompatible* way, that is along a different direction the packing responds by plastic deformation. The fragile state may be considered as a special case of jammed states, however, ordinary jammed matter may resist unidirected stress (below the yield stress) while fragile matter undergoes plastic deformation even to small incompatible stress. In this sense, the jammed state extends the Liu-Nagel jamming diagram [2, 3] in the limit of vanishing temperature. Since the pioneering work, Ref. [1], fragile jammed granular systems [26] have attracted significant scientific attention regarding both experimental [4–6] and theoretical/numerical [7–17] work.

Fragile states are generated from more dilute and mechanically unstable *unjammed* states, typically by application of shear [4]. By now the necessary and sufficient conditions for material properties and dynamical processes leading to jamming into a fragile state are unknown.

In this paper, by means of a rotating-drum experiment we will show that besides the widely discussed fragile state, there exists another, complementary state of jammed granular matter which we call *poly-directionally stable*. In this state of rather low density, the material responds to small stress elastically in a wide angular interval. The material is unstable against small stresses outside this angular interval – when loaded with small random stresses there is a constant probability of a plastic response leading to a sudden spatially located transformation of the material to a higher density which we call *collapse*. This new state is similar to the fragile state in that the system responds plastically or elastically in dependence on the direction of stress. The new state is different from the fragile state in that the angular range of elastic response is a wide interval whereas fragile matter responds

elastically only against small stresses in a particular direction or a very narrow interval while all other stresses lead to plastic response. Similar to the fragile state, polydirectionally stable states are a result of a dynamical process and the state is a result of the system's history.

Experimental setup: A thin cylinder of diameter 38 cm and width 0.4 cm rotates around its axis which is oriented perpendicular to the direction of gravity, Fig. 1. The cylinder is

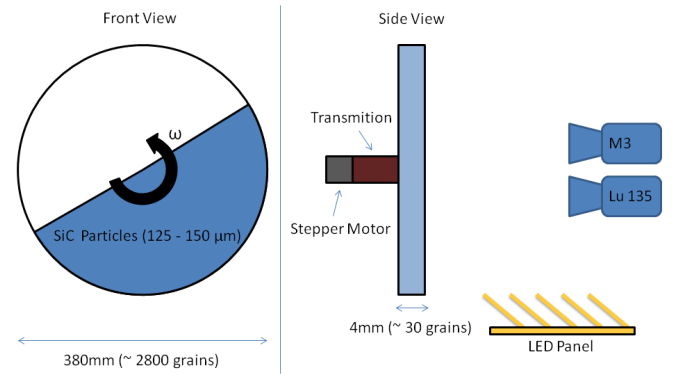


FIG. 1: Schematic drawing of the experimental setup.

half filled by about 400 g of sieved SiC granulate with grain size 125-150 μm . These particles are sharply edged and optically sparkling which allows for a convenient observation of particle motion. The cylinder consists of aluminium, front and backplane are made from glass coated with ITO to avoid static charges. The experiment is illuminated by a large LED panel producing enough light to record the grains' motion by a high-speed camera at 500 FPS and resolution 1280×1024 px and simultaneously by a standard CCD camera at 1 FPS. The cylinder rotates slowly at $1/7$ revolutions per minute. The angular velocity is chosen so that the granular material flows in steady motion on the free surface forming a narrow stripe of continuous flow such that there are neither avalanches nor stick-slip like flow. All results presented here are insensitive to the rotation velocity as long as the flow is uniform (no stick-slip) and the stripe of continuous flow is narrow. Except of this narrow region the material rests with respect to the cylinder, in particular the grains do not change their position in

respect to the particles in their neighbourhood. That is, the flowing stripe does not noticeably affect the material in the bulk of the granulate. Long intervals of the described type of motion are interrupted by **JO: instantaneous** consolidation events obeying a certain probability distribution where a large fraction of the material loses its mechanical stability and collapses.

Recurrent inflation and sudden collapse. Let us first look to the long-time behavior of the system. We apply Connected Component Labeling to the pictures taken in intervals of 1 sec (that is 0.86° of rotation) to evaluate the volume fraction occupied by particles and, thus, the average space filling. We pour in the material (assume random close packing (RCP)) and start the rotational motion at approximately horizontal free surface of the granulate. Initially, 263 cm^3 out of a total of 454 cm^3 are occupied by particles resulting in an average filling ratio $\eta = 0.58$.

After about two full revolutions the system relaxes to its stationary state characterized by an angle of about $\varphi_R = (38.1 \pm 0.1)^\circ$ between the free surface and the horizontal plane. To obtain this value, a straight line was fitted to the material surface in the left half of the cylinder. This value stays invariant during the entire experiment. (If not otherwise specified, we describe anti-clockwise rotation. It was checked that the behavior does not depend on the direction of rotation.) This stationary state is characterized by a steady narrow flow of grains downhill the free surface (flow regime) interrupted by sudden collapses of the sediment. During the flow regime the average space filling increases linearly with time by about 2 % while it shrinks due to a collapse event by about the same amount. Figure 2a shows the volume fraction over time for a total of 3.5 hours. From the magnification, Fig. 2b, we see that in the intervals between collapses the total volume increases linearly. Since we have a constant rotation rate and a uniform flux due to a constant inclination (except for a very short time just after the collapse) we conclude that the inflation results from the transfer of granular material of higher density, ρ_c , located at the right side of the cylinder into material of lower density, ρ_d , sedimented at the left side of the cylinder, where both ρ_d and ρ_c are homogeneous constants.

Comparing the images immediately before and after a collapse we notice that the density of the material does not change uniformly. Fig. 3 shows the image prior to the collapse **JO: (granular material appears dark, background bright)** overlayed by the image just after the collapse in inverse grayscale **JO: (granular material is bright)**. Thus, the dark area vanished due to the collapse. This dark area corresponds to the volume which was lost because of the transformation of loose material (low density, ρ_d) into material of higher density, ρ_c .

To estimate the ratio ρ_d/ρ_c we analyse the geometric shape of the volume region lost due to a particularly large collapse where we can assume that nearly all the material in the cylinder is of low density ρ_d (see below for a justification of this claim). The collapsed region is of approximately trapezoidal shape with $\alpha_d \approx 38.1^\circ$ and $\alpha_c \approx 36.4^\circ$ being the slope of the surface before and after the collapse and $h \approx 5.7 \text{ mm}$ is

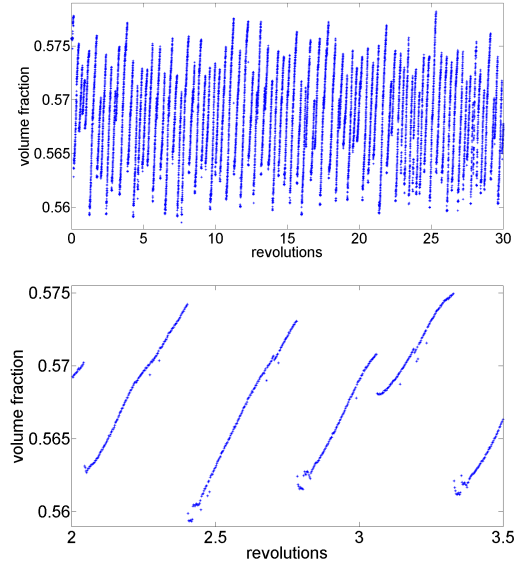


FIG. 2: Volume fraction as a function of time in the steady state. a) the total volume of the material varies by about 2% due to inflation in the steady flow regime and collapses. b) the same data for a shorter interval showing the inflation as a linear function of time. The data shown is only a small fraction of the total data used for the subsequent statistics, comprising several days of rotation. **TODO: a,b**

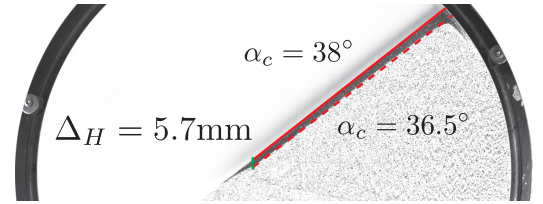


FIG. 3: a) Overlay of the images taken immediately before and after a collapse. The image prior to the collapse is drawn in reverse gray scale, thus, the bright area indicates the region which was occupied by material before the collapse and is empty after it. b) Magnification with straight lines fitted to the borders of the collapsed region. Here α_d and α_c indicate the slope of the surface before and after the collapse.

the height of the area. Note that we did not consider the area of the region right of the point where the surface touches the cylinder. We took this into account for the subsequent computation of ρ_d/ρ_c . The trapezoidal shape of the difference area together with the fact that the densities before and after the collapse are homogeneous constants leads to the conclusion that the collapsed region must also be of approximately trapezoidal shape. To check this we computed the velocity field by means of Particle Image Velocimetry (PIV) using the high speed recording of a collapse event (Fig. 4). The arrows show the cumulative velocity field summed up over the duration of the collapse. Note that this is not the flux since the material density changes during the collapse.

Let us now check the hypothesis that the collapsed region is of approximately trapezoidal shape. To this end we com-

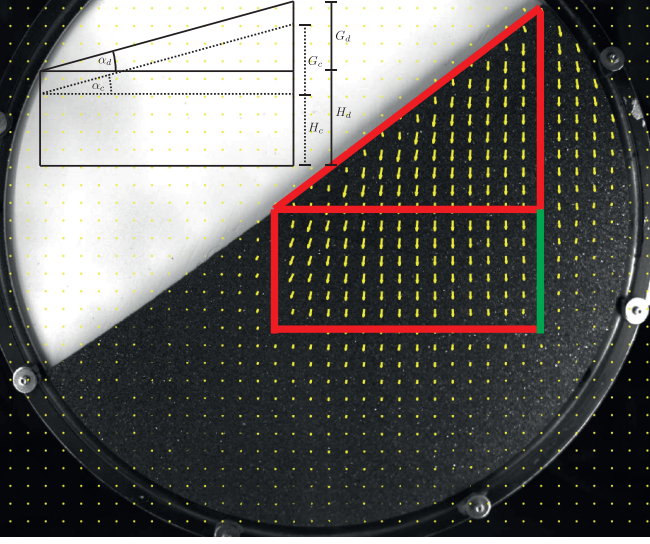


FIG. 4: Cumulative velocity field during a collapse obtained by PIV. The vector arrows are magnified for better visibility. The region of non-vanishing velocities indicate the volume which is affected by the collapse. The overlaid trapezoidal shape is obtained from our model calculation and agrees well with the experimental data.

pare the trapezoidal difference volume shown in Fig. 3b with the putative collapsed volume, sketched in Fig. ?? . The mass of low density material located in the triangle $\triangle(B, G_d)$ collapses into the triangle $\triangle(B, G_c)$:

$$\rho_c B^2 \tan \alpha_c = \rho_d B^2 \tan \alpha_d. \quad (1)$$

With $\alpha_c \approx 36.4^\circ$ and $\alpha_d \approx 38.1^\circ$ obtained from Fig. 3 we find $\rho_c/\rho_d = 1.0635$. Similarly, the material contained in the rectangle $\square(B, H_d)$ collapses into $\square(B, H_c)$:

$$\rho_c B H_d = \rho_c B H_c = \rho_c B (H_d - \Delta H) \quad (2)$$

$$H_d = \frac{\Delta H}{1 - \frac{\rho_d}{\rho_c}} \quad (3)$$

With $\Delta H \approx 5.7$ mm from Fig. 3 we obtain $H_d \approx 95.6$ mm which agrees well with the PIV results (see green bottom of the trapezoidal shape shown in Fig. 4) supporting our hypothesis.

The difference of more than 6% between the density of the collapsed state and the loose state may surprise, given that for spheres the difference between the packing fraction of random loose packing, $\rho_{RLP} \approx 0.55$, [18] and random close packing, that is, the densest non-crystalline state, $\rho_{RCP} \approx 0.64$ [19, 20] is about 15% [27]

As a general feature found in *all* collapse events analysed by PIV we notice that the region of densification is *always* restricted to the right hand side of the cylinder, that is, loose material which is rotated by less than $90^\circ - \varphi_R \approx 53.6^\circ$ was *always* found stable. Thus, *after* a collapse event, the region right of the cylinder's axis is collapsed, ρ_c , while left of the axis the material is in dilute state, ρ_d . Therefore, for the following we measure the rotation angle, Θ , with respect to the vertical line.

Instability of Packings. We analyze the series of collapses with respect to the distances between consecutive collapse events and obtain the histogram shown in Fig. 5.

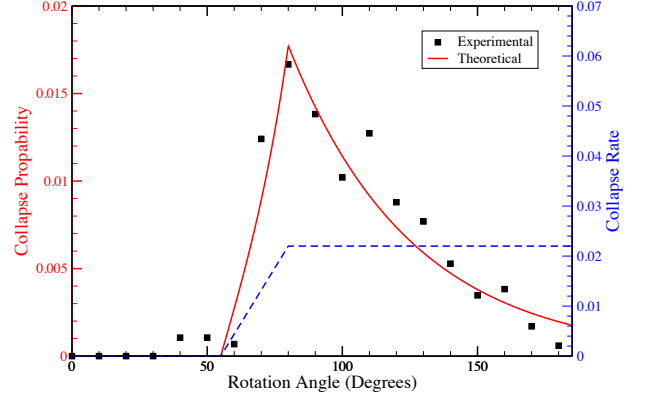


FIG. 5: Normalized frequencies of intervals between consecutive collapse events found in the experiment (points). Almost no collapses occur until the cylinder is rotated by about 60° after the preceding collapse. The solid line show the probability density, $p(\Theta)$, Eq. (5), based on the rate model, Eq. (4), sketched by the dotted line (right axis).

TODO: lower case, legende: experiment, theory, Eq. (xxx)

In the interval $0 \leq \Theta \lesssim 60^\circ$ after a collapse event we find almost no collapses, followed by a peak at $\Theta \approx 80^\circ$. This means that the loose material, ρ_d , is stable (insensitive with respect to small perturbations) in the corresponding orientation.

We model the system's behavior by a rate model,

$$r_c(\Theta) = \begin{cases} 0 & \text{for } 0 \leq \Theta \leq \Theta_0 \\ r_0 \frac{\Theta - \Theta_0}{\Theta_1 - \Theta_0} & \text{for } \Theta_0 \leq \Theta \leq \Theta_1 \\ r_0 & \text{for } \Theta \geq \Theta_1 \end{cases} \quad (4)$$

assuming that for $\Theta < \Theta_0$ the dilute material is stable and insensitive to small perturbations which are always present when the cylinder is rotated. For $\Theta > \Theta_1$ the material is oriented such that it left its angular range of stability and even a small perturbation may cause a collapse. The interval (Θ_0, Θ_1) demarcates a small transition region where the material gradually loses its stability. Using the rate $r_c(\Theta)$, we can compute the probability density for the next collapse event occurring at the angle Θ after the preceding collaps.

$$p(\Theta) = \begin{cases} 0 & \text{for } \Theta < \Theta_0 \\ r_0 \exp\left(\frac{r_0}{2} \frac{(\Theta - \Theta_0)^2}{\Theta_1 - \Theta_0}\right) \frac{\Theta - \Theta_0}{\Theta_1 - \Theta_0} & \text{for } \Theta_0 \leq \Theta < \Theta_1 \\ r_0 \exp\left(\frac{r_0}{2} (3\Theta_1 - \Theta_0)\right) & \text{for } \Theta \geq \Theta_1 \end{cases} \quad (5)$$

This distribution is shown in Fig. 5 (solid line) with $\Theta_0 = 60^\circ$ and $\Theta_1 = 80^\circ$ taken from the experimental result. The remaining free parameter, $r_0 = 0.022$, was determined by

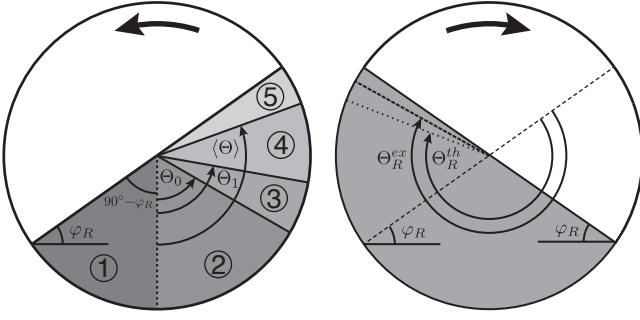


FIG. 6: Sketch of the described angles, φ_R , Θ_0 , Θ_1 , $\langle \Theta \rangle$, for the anticlockwise rotation (left) and Θ_r^{ex} , Θ_r^{th} or clockwise rotation (right). The ranges of granular matter in different states, “stable”, “collapsed or stable dilute”, “collapsed or unstable unstable dilute” and the interval (Θ_0, Θ_1) of the rate transition are also shown. For explanation see text.

equating the expectation value $\langle \Theta \rangle \equiv \int_0^\infty p(\Theta) \Theta d\Theta$, according to Eq. (5) with the average angle of rotation between collapses $\langle \Theta \rangle^{exp} \approx 108^\circ$ observed in the experiment. Without any further fit parameters we obtain very good agreement between the distributions of the intervals between collapses seen in the experiment and the results of the rate model, Eq. (4). Figure 6a sketches the described angles and ranges of stability.

Reversal of the rotation. To confirm our hypothesis on the wide angle of structural stability we reverted the sense of the rotation in the following way: We waited for a collapse-free interval of $90^\circ + \varphi_R$ such that we can expect that all material in the container is in the dilute state. We then gently stopped the motion. The flow at the surface ceased immediately keeping its slope φ_R with respect to the horizontal. At this point ($\Theta_r = 0$) we restarted the rotation in opposite direction. The surface flow restarted in the opposite direction at $\Theta_r \approx -2\varphi_R \approx -76^\circ$ **FZ.: $\varphi_R = 38^\circ$** when the material surface reached again the slope φ_R . Continuing the rotation the first collapse event was observed at $\Theta_r \approx -225.7^\circ$ (average over 10 repetitions); see Fig. 6a for a sketch of the process. Further continuing the rotation we found collapses at distances of $\Delta\Theta_r$, obeying the same statistics as reported before (see Fig. 5). This can be explained as follows: During the first interval $\Theta_r = 0 \dots -2\varphi_R$ there is no surface flow and, thus, there are no random perturbations caused by the narrow flow at the free surface. Consequently, albeit the dilute material (once sedimented due to previous anti-clockwise direction) is sensitive to random perturbations in this interval, we do not observe collapses there. At this point, $\Theta_r = -2\varphi_R$, the material is already rotated back to an extend such that it is *stable* to small perturbations and we should not expect a collapse of *this* material anymore. Continuing the rotation, for $\Theta_r < -2\varphi_R$ dilute material from the left side of the cylinder moves down the slope and consolidates at the right side. The sediment is also in the dilute state, but this time due to clockwise direction of the rotation. According to the arguments given above for the anti-clockwise motion, this material is stable for the next 52° **FZ.: 52**, that

is $\Theta_r \in (-2\varphi_R, -90^\circ - \varphi_R)$ until the dashed line in Fig. 6 turns vertical. From there, the expectation value for a collapse is $-\langle \Theta \rangle \approx -108^\circ$ according to Eq. (5), where the minus sign comes from the reversed sense of rotation. Summing up, from our arguments and the expectation value of $p(\Theta)$, Eq. (5), we predict $\Theta_r = -90^\circ - \varphi_R - \langle \Theta \rangle \approx -236^\circ$ **FZ.: $\Theta_r = 236$** for the expectation value of the next collapse. This result agrees with the experimentally determined value, $\Theta_r = -225.7^\circ$ up to about 4.5% **FZ.: 4.5%** and, thus, supports our hypothesis that the material is stable against small forces in a wide range of angular orientation and turns unstable outside this interval.

Conclusion. We investigated the structural stability of **JO: non-spherical, hard edged, polydisperse** granular matter in a narrow, slowly rotating cylinder. In this regime, the material flows homogeneously (no avalanches or stick-slip) in a small stripe down the slope due to a time-invariant angle of repose. In long-time recordings, we found that volume occupied by the material increases linearly in time, interrupted by sudden collapse events where the volume shrinks abruptly. By means of high-speed recordings and PIV we identified the range where due to a collapse the material densifies locally by about 6%, whereas the other part of the volume is unaffected by the collapse. From the linear increase of the volume with time in between collapse events we concluded that the during the sedimentation process dense (previously collapsed) material of constant density, ρ_c , is transformed into material of constant lower density, ρ_d .

Due to the downhill motion of the granulate the forces acting on the particles in the moment of consolidation are constant in amplitude and direction, determined by the angle of repose, φ_R and gravity. According to the rotation of the entire cylinder the material and, thus each grain, turns and thus feels static forces in directions different from the direction of forces at the moment of consolidation. This force is superimposed by random forces of very small amplitude mainly caused by the small region of downhill flow at the free slope.

Based on experimental observations of the angular intervals between collapses, we created a rate model, Eq. (4), stating that the material is stable with respect to perturbations in the angular interval $(0 \leq \Theta \leq \Theta_0)$ and unstable for $\Theta \geq \Theta_1$ with a small transition range (Θ_0, Θ_1) . From this model we computed the probability density, $p(\Theta)$, for the rotation $\Delta\Theta$ between successive collapses and found very good agreement with the corresponding normalized histogram of the experimental data without using any fit parameters. Using the rate model, verified with experimental data, we find that the sediment is stable against small perturbations in the range $\Theta \in (-90^\circ - \varphi_R, \Theta_1)$, that is, over a range of about 208° **FZ.: 208°**.

The entire chain of arguments was verified by application to a different process taking place when we revert the sense of orientation. Here we find agreement between experimental data and model prediction up to a deviation of about 4.5% **FZ.: 4.5%**.

Consequently, in this experiment we found a new state of dilute jammed granular matter which is stable against small

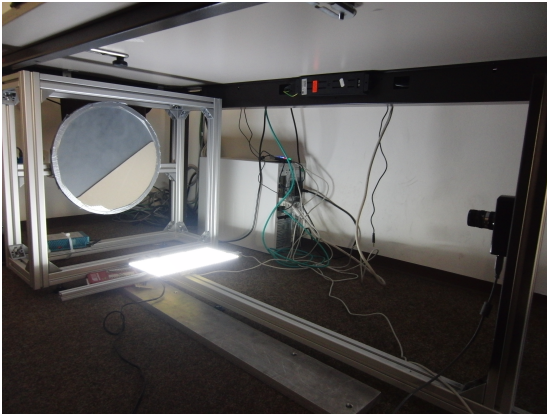
perturbation in a wide angular intervall of small stresses whereas it responds plastically when loaded with stresses outside this intervall. This state of *poly-directional stability*, thus, complements the earlier found *fragile* state [1].

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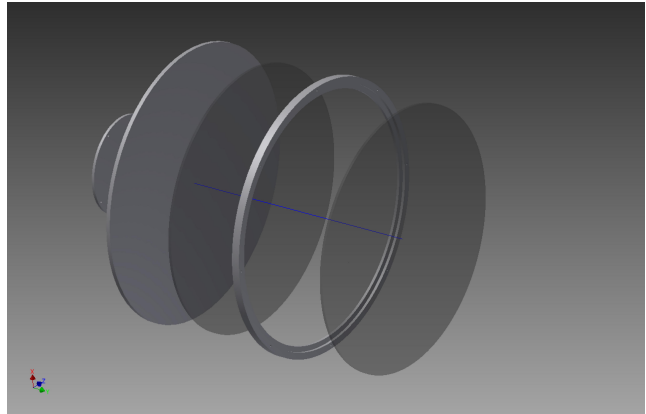
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 - [26] Note that the use of the term *fragile state* is different from [21, 22] where it denotes states which require cohesive interaction of the particles.
 - [27] The limit of stability corresponds to isostatic packings [23, 23] where the contact network is such that the number of degrees of freedom equals the number of forces. Here the density may adopt smaller values, however, such packings are less relevant since they do not emerge from dynamical processes in granular matter. Larger values than ρ_{RCP} may be obtained in tapping experiments [24, 25] where, however, crystalline regions appear which are not observed in our experiment.

A Versuchsaufbau

Der Versuchsaufbau besteht aus einem mit Granulat gefüllten Zylinder ($d_i = 390\text{ mm}$, $t = 4\text{ mm}$), der auf beiden Seiten mit einer Glasplatte verschlossen wird. Mit einer hochtransparenten, leitfähigen ($R_{\square} = 1.000\Omega$) ITO-Beschichtung (*Indiumzinnoxid*) der Platten, wird im Granulat auftretende Elektrostatik abgeleitet. Der Zylinder wird mit einer Nabe auf der Rückseite an eine Antriebseinheit bestehend aus einem Schrittmotor und einem Getriebe befestigt. Ein hohes Untersetzungsverhältnis ($i = 256$) ist notwendig, um die Trommel mit einer Geschwindigkeit von 0.1 U/min drehen zu können. Die Motorsteuerung unterteilt jeden Schritt des Motors in bis zu 64 Mikroschritte und ermöglicht dadurch eine gleichmäßige Bewegung. Dies ist wichtig, da das Granulat im instabilen Zustand empfindlich auf die Einleitung von äußeren Kräften reagiert. Für die Datenerfassung wird eine CCD-Kamera (Lucam LU135) mit einer Auflösung von 1392×1040 verwendet. Die Versuchsdauer soll bis zu 24 Stunden betragen, weshalb das Experiment automatisiert werden muss. Über eine USB-Schnittstelle wird die Kamera mit einem MATLAB Skript gesteuert und schießt ca. 1 Bild pro Sekunde. Um das Experiment vor Sonneneinstrahlung zu schützen, wird dieses durch einen Vorhang verdunkelt und mit einem 20 W LED-Panel beleuchtet. Da dies bei konstanter Beleuchtung jedoch einen erheblichen Wärmeeintrag bedeuten würde, wird das Panel mit einem IO-Board (Meilhaus RedLab 1008) an das Skript gekoppelt. Der Ablauf des Programms ist in Abbildung A.2 schematisch gezeigt. Mit dieser Methode wird der Wärmeeintrag um ca. 90% reduziert.



(a) Versuchsaufbau mit Beleuchtung



(b) Explosionszeichnung der Trommel

Abbildung A.1: Versuchsaufbau

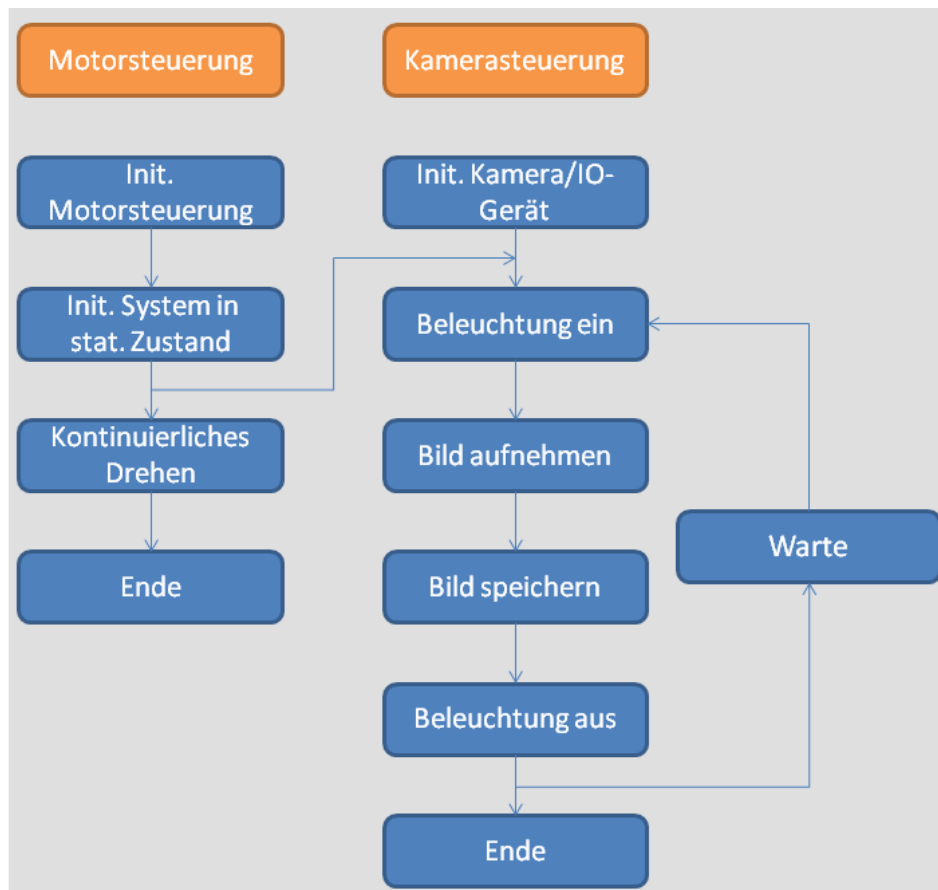


Abbildung A.2: Ablaufdiagramm des Skripts für die Steuerung des Versuchs

A.1 MATLAB Code zur Steuerung des Versuchs

```

1 function Lucam_Matlab
2 %-----
3 %Skript zur Steuerung der Kamera und der Beleuchtung, es werden die von Windows
   fuer die Kamera, und die von Meilhaus fuer das RED-LAB zur Verfuegung
   gestellten Treiber verwednet.
4 %-----
5 %Kamera Initialisierung
6 nBilder=200000; %Anzahl der gewuenschten Bilder
7 vid = videoinput('winvideo', 1, 'RGB24_1392x1040');
8 src = getselectedsource(vid);
9 vid.FramesPerTrigger=1;
10 %IO-Board Initialisierung
11 dio = digitalio('mcc',0);
12 addline(dio,0:7,'out');
13 %Setze Bit fuer Digitalen Ausgang 1
14 Loff = [1 0 0 0 0 0 0 0];

```

```

15 Lon = [0 0 0 0 0 0 0 0 ];
16 putvalue(dio,Loff); %Beleuchtung aus
17 phtinkr=1;
18 averagetime=0;
19
20 for i = 1:nBilder
21     tic; %Start Timer
22     putvalue(dio,Lon);%Beleuchtung ein
23     pause(0.1); %Warte nach Anschalten der Beleuchtung, bzw. Streckung des
        Intervalls zwischen den Aufnahmen
24     start(vid);
25     filename = sprintf('C:\fabian\Measurement\SiC-256Hz-001\images\Bild%d.jpeg',
        phtinkr)
26     imwrite (getdata (vid),filename ); %Bild aufnehmen
27     putvalue(dio,Loff);%Beleuchtung aus
28     phtinkr=phtinkr+1;
29     toc; %End Timer
30     averagetime=averagetime+toc/i
31     save('C:\fabian\Measurement\SiC-256Hz-001\data.txt', '-append -ascii -tabs',
        averagetime);
32 end
33 end

```

B Methoden der Bildauswertung

B.1 Connected-Component-Labeling

Für die Auswertung werden die Bilder in MATLAB eingelesen. Allgemein interpretiert MATLAB diese als Matrizen, deren Elemente die Helligkeitswerte (z.B. Graustufen 0-255) der einzelnen Bildpunkte aufweisen. Ein Schwarz/Weiß Bild wird wie in Abbildung B.1 eingelesen. Die Bildauswertung basiert auf dem Connected-Component-Labeling Algorithmus. Dieser sucht in einer Matrix nach Einträgen mit einem vorgegebenen Wert und gruppiert diese gegebenenfalls unter der Voraussetzung, dass die Einträge benachbart sind. In dem in MATLAB implementierten Algorithmus wird standardmäßig eine Abfrage aller 8 direkt angrenzenden Nachbareinträge durchgeführt, Abbildung B.2. Anhand der in Abbildung B.1 gezeigten Matrix wird das Verfahren nun verdeutlicht, Abbildung B.1. Werden in der Umgebung um den ersten gefundenen Eintrag weitere Elemente erkannt, so werden diese gruppiert und davon ausgehend weitere angrenzende Einträge untersucht. Mit diesem Verfahren ist es möglich neben der Begrenzungslinie des Gebietes auch dessen Flächeninhalt zu berechnen [Edd07].

Im vorliegenden Fall soll der Flächeninhalt der vom Granulat bedeckten Fläche errechnet werden. Da sowohl das Siliziumcarbid als auch der Aluminiumring einen sehr niedrigen Helligkeitswert aufweisen, wird zunächst der Flächeninhalt der nicht bedeckten Fläche ermittelt. Diese lässt sich durch den hellen Hintergrund einfach vom Ring und dem Granulat abgrenzen. Zuerst wird der Bearbeitungsbereich grob auf die freie Fläche maskiert und das Bild in ein Schwarz/Weiß Bild konvertiert. Daraufhin kann der CCL-Algorithmus angewandt werden. Abbildung B.5 zeigt das ursprüngliche Bild mit der Begrenzungslinie und dem berechneten Flächeninhalt. Da die Gesamtfläche bekannt ist, kann daraus die gesuchte Fläche errechnet werden.

Eine frühere Auswertemethode nutzte eine Maske, die den Bearbeitungsbereich exakt auf das Innere der Trommel beschränkte. Dadurch musste der CCL-Algorithmus lediglich die Kante an der freien Fläche erkennen, die Außengrenzen waren durch die Maske gegeben. Das Ergebnis dieser Auswertung ist in Abbildung B.4(a) zu sehen. Der Volumenanteil der bedeckten Fläche schwang stark über der Zeit, was jedoch durch Beobachten des Experimentes nicht bestätigt werden konnte. Um zu überprüfen, ob die sich die Trommel durch eine ungenaue Positionierung der Nabe exzentrisch um die Motorachse dreht, wurde die vertikale Position eines Randpunktes aufgezeichnet. Abbildung B.4(b) zeigt, dass der Randpunkt eine Vertikale Bewegung durchführt. Die Trommel bewegt sich also exzentrisch um die Motorachse. Eine Bildauswertung mit einer starren Maske ist also nicht möglich.

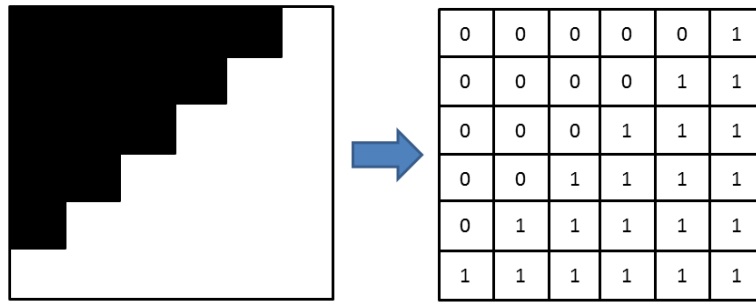


Abbildung B.1: Matrixinterpretation eines SW Bildes

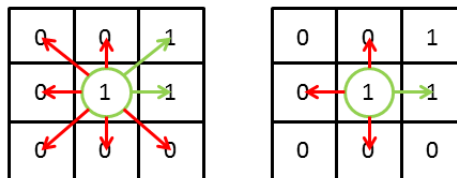


Abbildung B.2: Nachbarschaftskriterium mit 8 und 4 Elementen [Edd07]

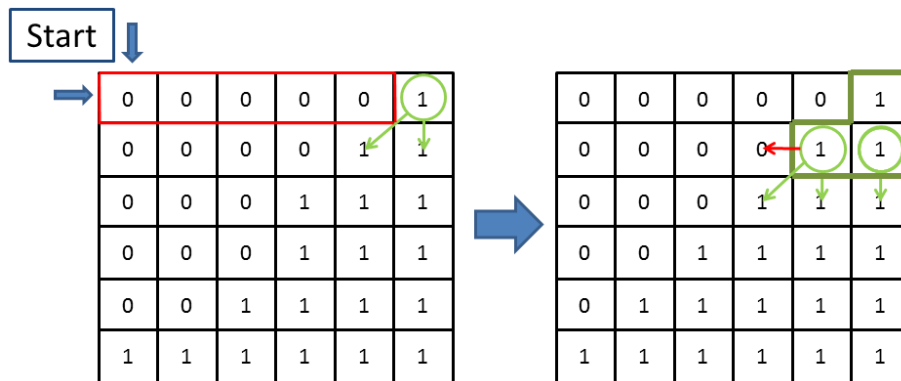
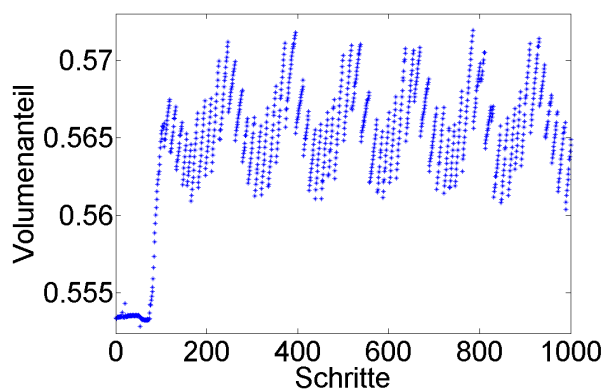
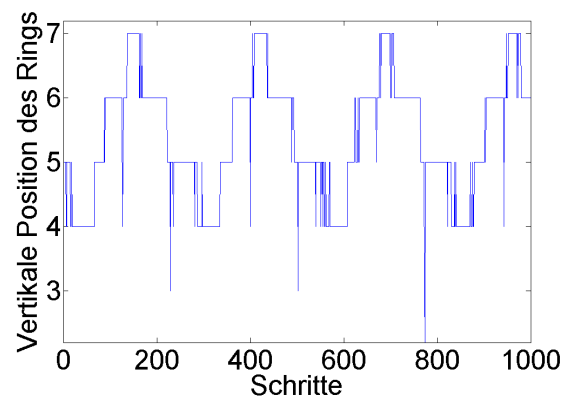


Abbildung B.3: Schematische Darstellung des CCL-Algorithmus



(a) Anteil der bedeckten Fläche



(b) Vertikale Position des Rings

Abbildung B.4: Datenanalyse der exzentrischen Trommel

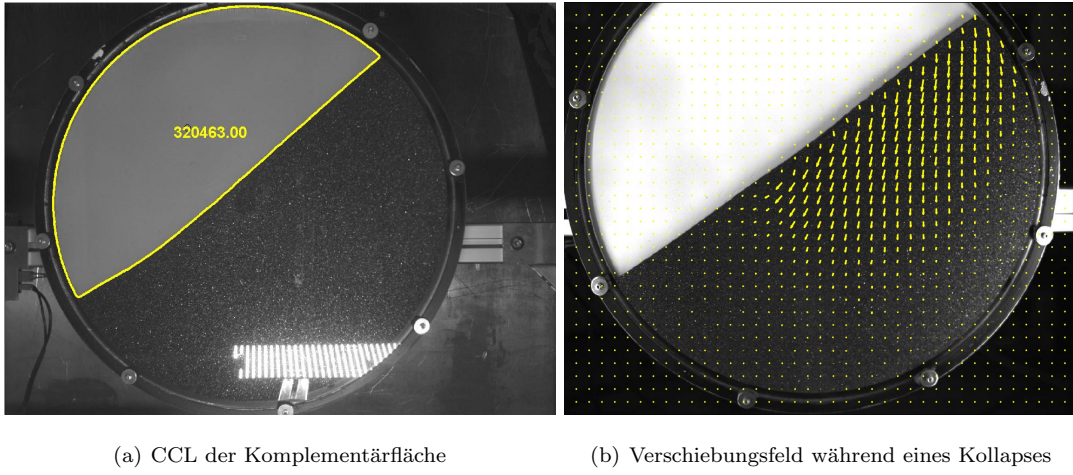


Abbildung B.5: Visualisierung der Bildauswertungen

B.2 Hochgeschwindigkeitsaufnahmen

Eine Hochgeschwindigkeitskamera wird eingesetzt, um das System während eines Kollapses zeitlich hoch aufgelöst analysieren zu können. Zum Einsatz kommt eine Motionscope M3 Kamera mit einer Auflösung von 1280x1024 bei 500 fps. Da Ein Kollaps nicht vorhersehbar ist wird diese mit einem manuellen Post-Trigger ausgelöst. Dafür speichert die Kamera kontinuierlich Daten in einem Zwischenspeicher. Wird der Trigger ausgelöst, so werden auch die Bilder kurz vor dem Ereignis gespeichert. In einem Intervall von ca. 40 Bilder ist die Dynamik des Kollapses zu sehen, was einer Zeitspanne von 0.04 s entspricht

B.3 Particle Imageing Velocimetry (PIV)

PIV ist eine Methode zur Visualisierung von Verschiebungsfeldern. Im konkreten Fall wird ein Bild in Teilgebiete der Größe 32x32 Pixel, so genannten *interrogation spots*, untergliedert, Abbildung B.6. Wendet man die Kreuzkorrelationsfunktion B.1 auf das gleiche Gebiet zweier aufeinanderfolgender Bilder an, ergibt sich der Verschiebungsvektor dieses Gebietes [Pra00]. Diese Funktion wird für jedes dieser Gebiete bestimmt und man erhält somit ein Vektorfeld, das die lokale Verschiebung des Granulates widerspiegelt. Summiert man die Vektoren aller während des Kollapses entstandenen Felder auf, so erhält man das kumulierte Verschiebungsfeld, Abbildung B.5(b). Hieraus ist zu erkennen, dass während eines Kollapses nur ca. die Hälfte des Granulates eine Verschiebung erfährt. Die globale Dichteänderung von 2 % lässt sich damit auf eine lokale Änderung der Dichte reduzieren, die im Bereich von ca. 4 % liegt.

$$R_{\Delta x \Delta y} = \sum_i \sum_j I(i, j) \cdot I'(i + \Delta x, j + \Delta y) \quad (\text{B.1})$$

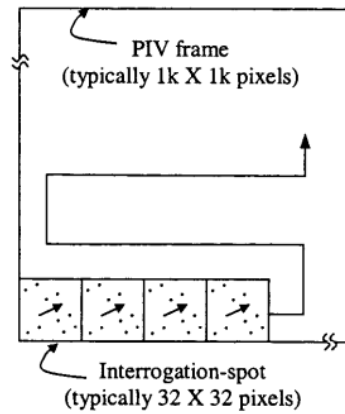


Abbildung B.6: Einteilung des Bildes in Untereinheiten

[Pra00]

B.4 MALTAB Code der Bildauswertung

```

1 function result = Bildverarbeitung(i)
2 %-----
3 % Skript zur automatischen Auswertung der Bilder. Die Bildverarbeitung basiert
   auf dem CCL-Algorithmus. Das Skript bekommt als Uebergabeparameter den Index
   des aktuell auszuwertenden Bildes.
4 %-----
5     mask = imread('mask.jpg'); %Maske einlesen
6     bilder =sprintf('Bild\%d.jpeg',i);
7     bilder % zeige aktuellen Bildindex an
8     %read image
9     sample = imread(bilder);
10    level = graythresh(sample);
11    mask = im2bw(mask); %Maske in SW umrechnen
12    sample_bw = im2bw(sample,0.28); %Aktuelles Bild in SW-Bild mit Schwellwert
        umrechnen
13    sample_bw = imfill(sample_bw,'holes'); %Maskieren und fehlstellen ausfuellen
14    sample_bw = sample_bw .* mask;
15    [B,L]=bwboundaries(sample_bw); %CCL, Flaeche L und Grenzen B
16    stats = regionprops(L,'Area','Centroid'); %Flaecheninhalte und Schwerpunkt
        der Flaeche L
17
18    for k = 1:length(B)
19        boundary = B{k};
20        area=stats(k).Area; %Flaeche berechnen
21        area_string = sprintf('\%2.2f',area);

```

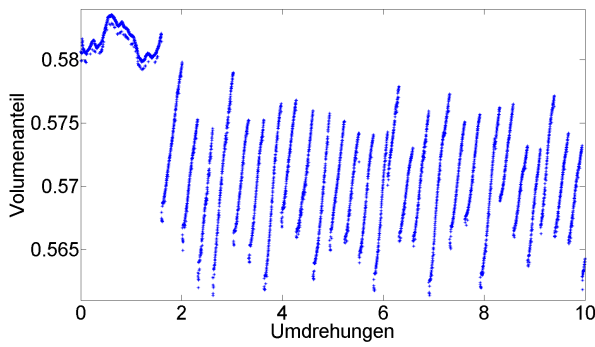
```

22     if area > 3000
23         hold on
24         boundary = B{k};
25         centroid = stats(k).Centroid;
26         text(centroid(1)-35,centroid(2)+13,area_string,'Color','y','FontSize
           ',14,'FontWeight','bold');
27         result = cat (2, centroid , area);
28         display(result);
29         save 'C:\Bildauswertung\result.txt' result -append -ascii -tabs; %
           Ergebnisse speichern
30     end
31 end
32 end

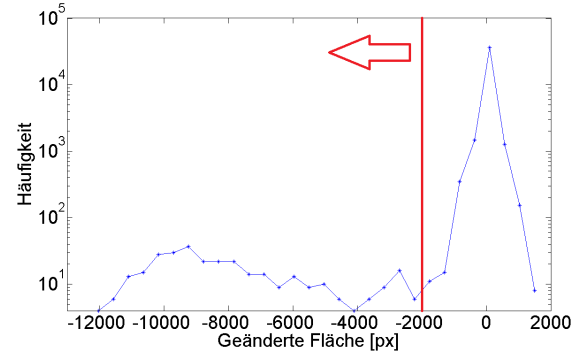
```

C Datenanalyse

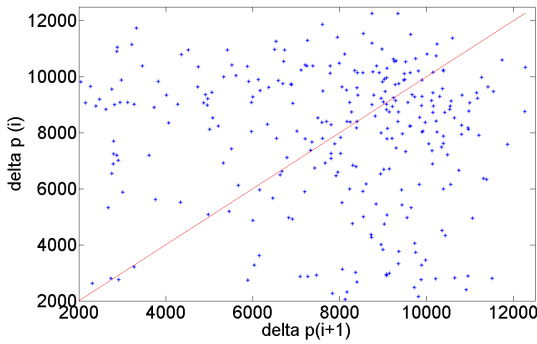
Das Ergebnis der Bildauswertung ist in Abbildung C.1(a) zu sehen. Das System geht nach ca. 2 Umdrehungen in den im Manuskript beschriebenen Zustand über. Die ermittelten Daten sollen nun überprüft und näher analysiert werden. Zunächst soll bestimmt werden, wie weit das System nach einem Kollaps gedreht werden muss, um einen Weiteren zu erhalten. Dafür wird ein über 10 Stunden gewonnener Datensatz analytisch abgeleitet und davon ein Histogramm erstellt, Abbildung C.1(b). Wir definieren einen nennenswerten Zusammenbruch ab einer Abnahme der besetzten Pixel von $x \leq -2000 px$. Zunächst muss überprüft werden, ob die Daten dieser Zusammenbrüche miteinander korrelieren. Dazu wird eine Korrelationsmatrix erstellt, Abbildung C.1(c). Sollte eine Abhängigkeit der Datenpunkte untereinander bestehen, so würden diese sich in der Matrix gehäuft um die Winkelhalbierende befinden. Eine breite Verteilung der Punkte auf der Matrix zeigt an, dass keine Abhängigkeiten zwischen Datenpunkten besteht. Somit kann der Winkel zwischen zwei aufeinanderfolgenden Kollapsen berechnet werden, Abbildung C.1(d).



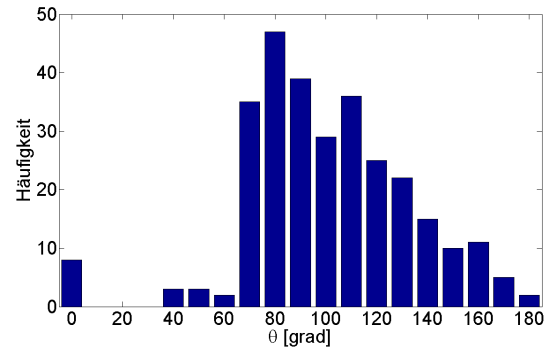
(a) Muster der Zusammenbrüche mit Übergangszone



(b) Histogramm der geänderten Fläche



(c) Korrelationsdiagramm der Daten aus Diagramm (b) mit $x \leq -2000 px$



(d) Winkel θ zwischen zwei aufeinanderfolgenden Kollapsen

Abbildung C.1: Datenanalyse

C.1 MATLAB Code der Datenanalyse

```
1 function Datenauswertung_Rotating_Drum
2
3 daten=load('result-SiC-longterm-256Hz.txt'); %Lade Daten
4 area_corr=(766000-daten(:,3)); %Errechne von Granulat bedeckter Flaeche
5 %Analytische Ableitung bestimmen
6 for i=1:length(area_corr)-1
7     ableitung(i)=area_corr(i+1)-area_corr(i);
8 end
9 %-----
10 i=1;
11 j=1;
12 k=0;
13 erster=1;
14 abstand=[];
15 letzterkollaps=0;
16
17 while i<length(ableitung)
18     if ableitung(i)< -2000 %2000 Als Grenzwert fuer Kollaps
19         if erster<1
20             abstand(j)=k-letzterkollaps;
21             neu_Flaechaenderung(j)=-ableitung(i);
22             %Umrechnung photos in Zeit u Drehwinkel
23             %-----
24             timepicture= 0.8572;
25             min_rev = 400/60;
26             time = abstand(j)*timepicture/60;
27             fraction = min_rev ./ time;
28             degr_of_collapse = 360 ./ fraction;
29             zeitabstand(j)=degr_of_collapse;
30             %-----
31             j=j+1;
32         end
33         erster=0; %Erster Kollaps ausnehmen
34         letzterkollaps=i;
35         k=0;
36     end
37     i=i+1;
38     k=k+1;
39 end
```

```

40 mean(zeitabstand);
41
42 %PLOT DATA
43 %-----
44 figure(1) %Subplotmatrix
45 subplot(1,2,1),plot(zeitabstand,'*');
46 hold on;
47 %Filterinput definieren und anwenden
48 filterdim=ones(1,16)/16;
49 filterpar=1;
50 filteredData=filter(filterdim,filterpar,zeitabstand);
51 %-----
52 subplot(1,2,2),plot(filteredData);
53 set(gca,'FontSize',30);
54 ylabel ('\alpha [deg]'); %rotation angle between collapses
55 xlabel ('number of collapse');
56 title ('Gleitender Mittelwert (Ordnung16)');
57 ylim([50 200]);
58 %-----
59 figure(2)
60 bar(0:10:200,histc(zeitabstand,0:10:200))
61 set(gca,'FontSize',30);
62 set(gca,'XTick',0:10:180)
63 ylabel('#');
64 xlabel ('\alpha [deg]');
65 xlim([-5 185]);
66 %-----
67 figure(3)
68 for i=1:length(neu_Flaechaenderung)-1
69     xwerte(i)=neu_Flaechaenderung(i);
70     ywerte(i)=neu_Flaechaenderung(i+1);
71
72 end
73 winkelhalb=0:1:max(ywerte);
74 plot(xwerte,ywerte,'*');
75 hold on;
76 plot(winkelhalb,'r');
77
78 set(gca,'FontSize',30);
79 xlabel('delta_p(i+1)');

```

```

80 ylabel( 'delta_p(i) ');
81 %-----
82 figure(4)
83 [n,binloc]=hist(ableitung,30);
84 semilogy(binloc,n+1,'*');
85 set(gca,'FontSize',30);
86 end

```

Im Folgenden werden die Datenblätter der relevanten Systemkomponenten angehängt. Um reproduzierbare Ergebnisse zu erhalten sollten diese Komponenten verwendet werden.



■ Closed Loop Motor-Controller mit Encodereingang, SMCi33



Technische Daten

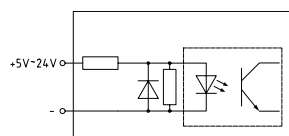
Betriebsspannung:	12 bis 48 V DC
Phasenstrom:	Nennstrom 2 A, einstellbar bis max. 3 A / Phase
Schnittstelle:	RS485 oder USB
Betriebsart:	Position, Drehzahl, Flagposition, Takt-Richtung, Analog, Joystick
Betriebsmodus:	1/1, 1/2, 1/4, 1/5, 1/8, 1/10, 1/32, 1/64, Adaptiv (1/128)
Schrittfrequenz:	0 bis 50 kHz im Takt-/Richtungsmodus, 0 bis 25 kHz in allen anderen Modi
Eingänge:	6 Optokopplereingänge (5 - 24 V)
Ausgänge:	3 Open Collector, 30 V / 30 mA max.
Positionsüberwachung:	automatische Fehlerkorrektur bis 0,9°
Stromabsenkung:	einstellbar 0- 100%
Schutzschaltung:	Überspannung, Unterspannung und Kühlkörpertemperatur > 80 °C
Temperaturbereich:	0 bis +40 °C

* Phönix-Stecker sind im Lieferumfang enthalten.

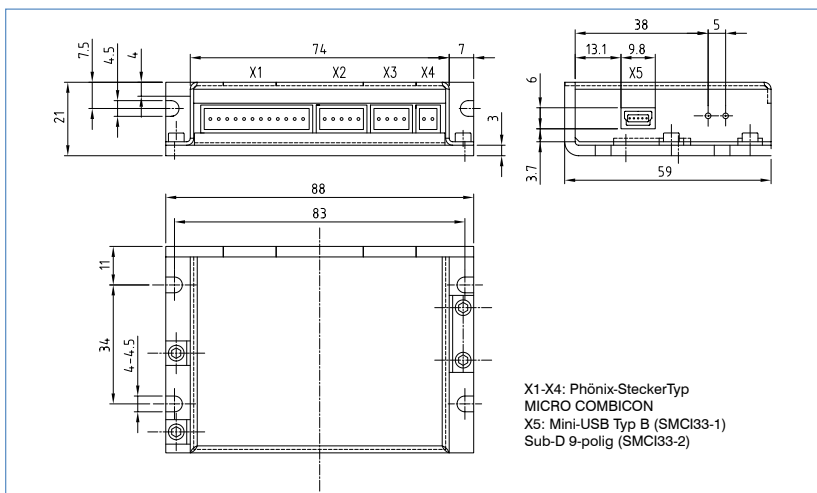
! Achtung: Verwenden Sie immer einen Stützkondensator für die Betriebsspannung der Steuerung. Dieser sollte so nah wie möglich an die Steuerung platziert werden. Steuerungen bis 4 A benötigen einen 4700µF und Steuerungen bis 10 A benötigen einen 10.000µF Kondensator. Andernfalls besteht die Gefahr der Zerstörung der Steuerung.

Eingangsbeschaltung

Optokoppler



Maßbild (mm)



Ein/Ausgänge (X1)

Pin	Funktion
1	Input1
2	Input2
3	Input3
4	Input4
5	Input5
6	Input6
7	Com
8	Output 1
9	Output 2
10	Output 3
11	Analog In
12	GND

Encoder (X2)

Pin	Funktion
1	+5V
2	CH-B
3	CH-A
4	INDEX
5	GND

Motor Anschluss (X3)

Pin	Funktion
1	Motor Spule A
2	Motor Spule A\
3	Motor Spule B\
4	Motor Spule B

Versorgung (X4)

Pin	Funktion
1	UB24-48V
2	GND

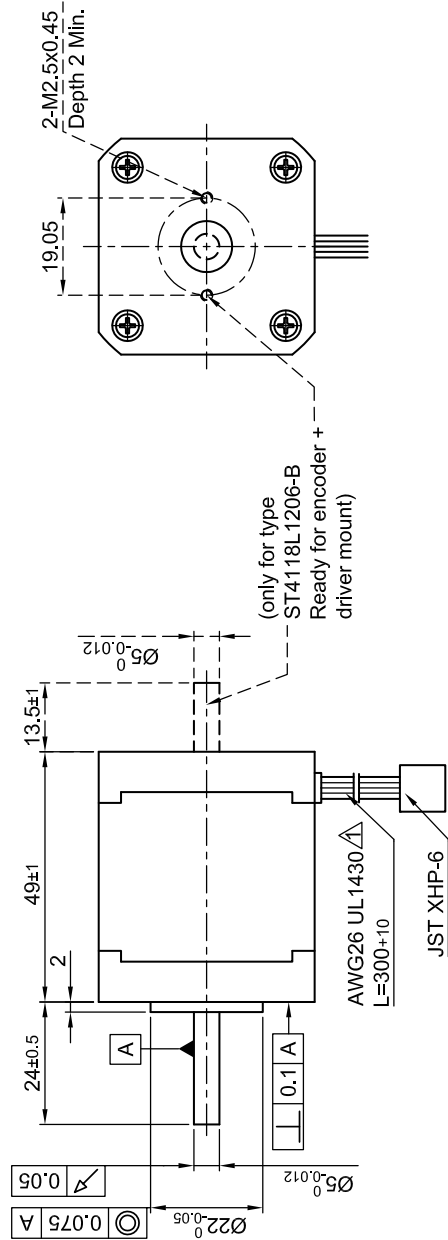
SMCi33-2: RS485 (X5)

Pin	Funktion
1	NC
2	RX+
3	+5V
4	TX+
5	N.C.
6	N.C.
7	RX-
8	GND
9	TX-

SMCi33-1: USB (X5)
USB-Standard

Bestellbezeichnung

SMCi33 -
1= USB
2= RS485



SPECIFICATION		CONNECTION		PERMISSIBLE RADIAL+AXIAL FORCE	
VOLTAGE (VDC)		BIPOLAR OR BIPOLAR-1 WINDING		BIPOLAR SERIAL	
AMPS /PHASE		4.0		5.6	
RESISTANCE/PHASE (Ohms)@25°C		1.2		0.85	
INDUCTANCE/PHASE (mH) @1KHz		3.3±15%		6.6±15%	
HOLDING TORQUE (Nm) [lb-in]		3.4±20%		13.6±20%	
DETENT TORQUE (Nm) [lb-in]		0.35 [3.1]		0.495 [4.381]	
STEP ANGLE (°)		1.37x10 ⁻² [0.1212]			
STEP ACCURACY (NON-ACCUM)		1.8			
ROTOR INERTIA (kg-m ²) [lb-in ²]		±5%			
WEIGHT (kg) [lb]		8.2x10 ⁻⁶ [2.8x10 ⁻²]			
TEMPERATURE RISE: MAX.80°C (MOTOR STANDSTILL; FOR 2 PHASE ENERGIZED)		0.34 [0.75]			
AMBIENT TEMPERATURE -10°~ 50°C [14°F ~ 122°F]					
INSULATION RESISTANCE 100 Mohm (UNDER NORMAL TEMPERATURE AND HUMIDITY)					
INSULATION CLASS B 130° [266°F]					
DIELECTRIC STRENGTH 500VAC FOR 1 MIN. (BETWEEN THE MOTOR COILS AND THE MOTOR CASE)					
AMBIENT HUMIDITY MAX. 85% (NO CONDENSATION)					

Diagram illustrating the mechanical structure and forces acting on the motor. Labels include BEARING, ROTOR SPRING-MOUNTED IN AXIAL DIRECTION, SPRING WASHER, and forces F_a and F_r .

WIRING DIAGRAM showing connections for (A)BRN, (COM)BLK, (A)ORG, (B)RED, (COM)WHT, and (B)YEL.

for >speed
for <speed

FULL STEP 2 PHASE-Ex.,
WHEN FACING MOUNTING END (X)

STEP	CCW				CW
	A	B	A\	B\	
1	+	+	-	-	
2	-	+	+	-	
3	-	-	+	+	
4	+	-	-	+	

Nanotec®
PLUG & DRIVE

ST4118L1206

STEPPING MOTOR

			DWG.NO
W.	29.11.06		

SIGNATURE

ST4118L1206

1.4 Megapixel USB 2.0 Camera


Outline

Lumenera's Lu130 and Lu135 series of megapixel cameras are designed to be used in a wide variety of applications, particularly in low-light conditions.

With 1392x1040 resolution and on-board processing these cameras deliver outstanding image quality and value for industrial and scientific imaging applications.

Electronic global shutter provides capabilities similar to a mechanical shutter, allowing simultaneous integration of the entire pixel array. This is ideal for capturing objects in high-speed motion.

Uncompressed images in live streaming video and still image capture are provided across a USB 2.0 digital interface. No framegrabber is required. Advanced camera control is available through a complete Software Developer's Kit (SDK), with sample code available to quickly integrate camera functions into OEM applications.

Hardware and software based synchronization trigger is provided standard. Camera models are offered in both enclosed (Lu135) and board-level (Lu130) form. Custom form factor (sizes) as well as color and monochrome camera models are available.

All Lumenera products are supported by an experienced team of software developers and application engineers. We understand your imaging needs and are here to help you with your integration and development.

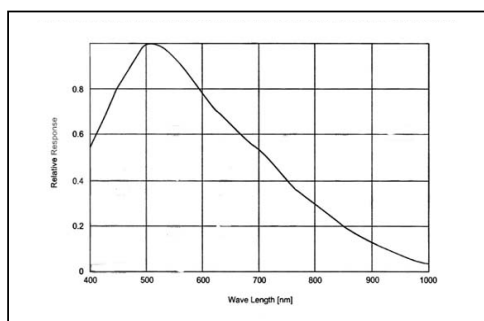
Performance Features

- ☐ High quality CCD sensor
- ☐ Excellent sensitivity with high color reproductivity
- ☐ Color or monochrome, interline transfer progressive scan, 1.4 megapixel CCD sensor
- ☐ High-speed USB 2.0 (480Mbits/sec)
- ☐ 15 fps at full 1392x1040 resolution
30 fps 640x480
- ☐ Binning and Region of Interest (ROI) options improve sensitivity and provide higher frame rates
- ☐ Global shutter for capturing fast moving objects and strobe lighting
- ☐ GPIOs for control of peripherals and synchronization of lighting (4in/4out)
- ☐ FCC Class B, CE Ready
- ☐ RGB Bayer video output
- ☐ Select 8 or 12-bit pixel data
- ☐ Simplified cabling - video and full camera control over a single USB cable
- ☐ C-Mount provided
- ☐ DirectShow compatible
- ☐ USB cameras are software compatible with Windows™ XP, Windows Vista and Windows 7, 32 and 64-bit operating systems
- ☐ Complete SDK available
- ☐ Full one (1) year warranty

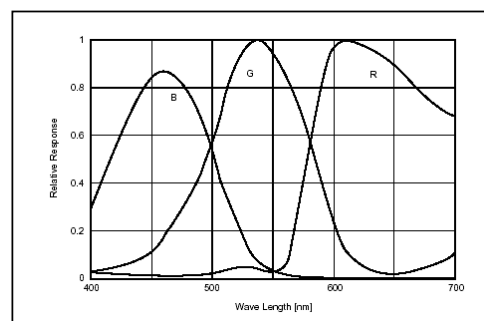
Specifications

Lu130/Lu135

Image Sensor	1/2" format, color or mono, 6.5mm x 4.8mm array
Effective Pixels	1392x1040, 4.65 μ m square pixels
Frame Rate	15 fps at 1392x1040, 30 fps with binning (2x - 4x)
Sensitivity	High
Dynamic Range	60dB
White balance	Manual
Exposure	Manual
Dimensions (W x H x D)	2.25 x 3.85 x 1.56 inches (enclosed) 2.00 x 2.50 x 1.63 inches (board level)
Mass	~150g / 300g
Power Requirement	USB bus, optional external 5VDC, 500mA (not included)
Power Consumption	~2.5 Watts
Operating Temperature	0°C to +50°C
Operating Humidity	5% - 95%, Non-condensing
Interface Connector	Standard USB cable
Lens Mount (Lens not included)	C-Mount (CS-Mount option)



Mono Response Curve



Color Response Curve

***Full customization
available to meet your
exact needs!***

Ordering Information

Lu130M	– Monochrome Camera Module
Lu130C	– Color Camera Module
Lu135M	– Enclosed Monochrome Camera
Lu135C	– Enclosed Color Camera
LuSDK	– Developer's Kit and Accessories

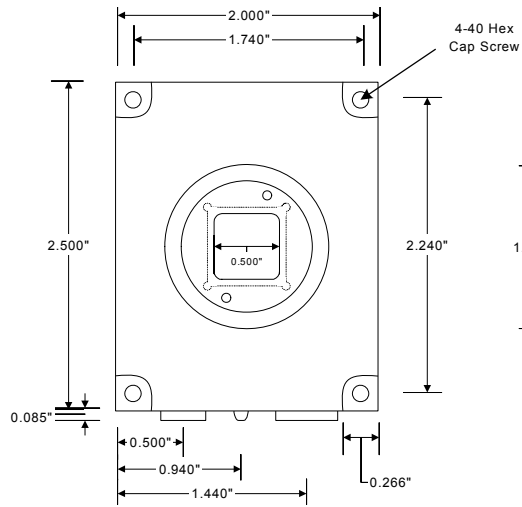
Lumenera Corporation • 7 Capella Court, Ottawa, ON, Canada K2E 8A7 • (t) 1.613.736-4077 • (f) 1.613.736.4071 • www.lumenera.com

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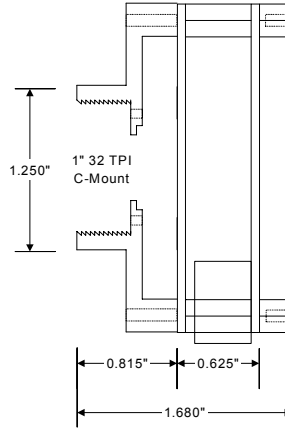
Mechanicals

Lu130/Lu135

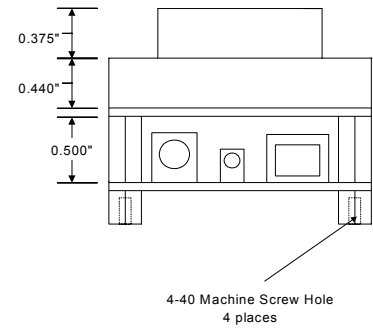
OEM Board-Level Camera



Front



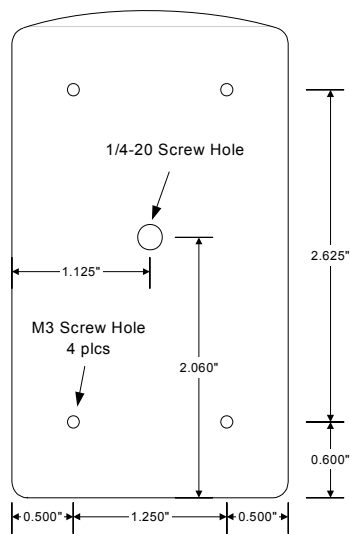
Side



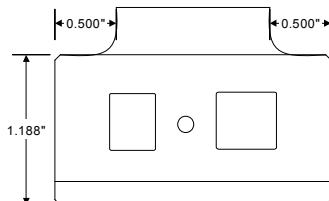
Bottom

Enclosed Camera*

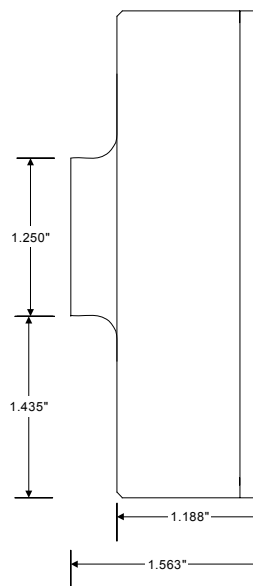
Back



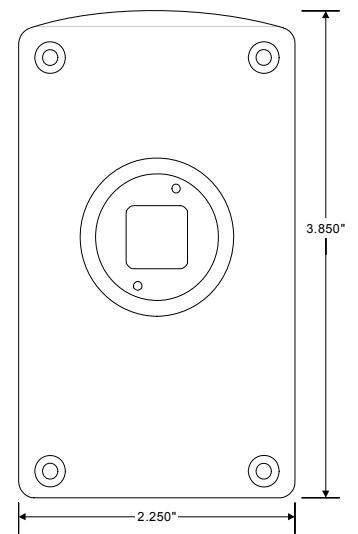
Bottom



Side



Front



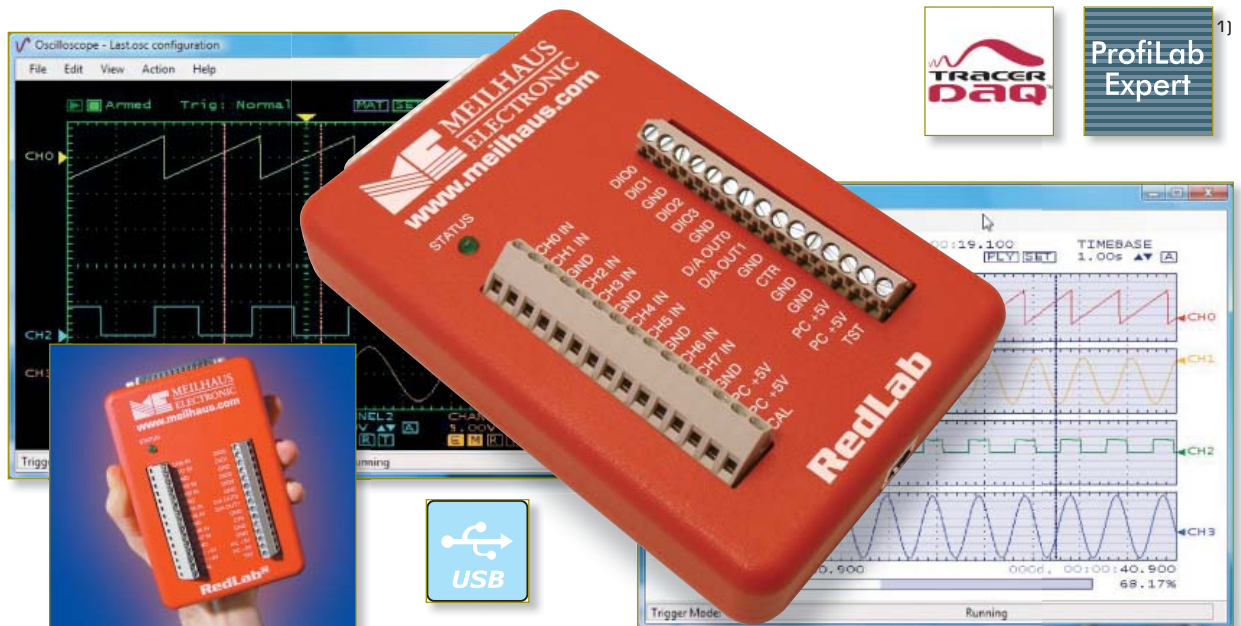
* Anodized aluminum, std color - black

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Preiswertes, komplettes 12 bit USB-Mini-Messlabor

RedLab 1008, RedPack 1008



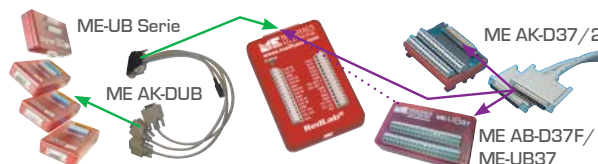
- ☐ Eines der meistverkauften Allround-Mess-Labore.
- ☐ 8 single-ended oder 4 differenzielle Analog-Eingänge, 12 bit A/D-Wandlung, bis 1,2 kS/s.
- ☐ 2 Analog-Ausgänge, 10 bit.
- ☐ 24 Digital-I/O-Kanäle. Erweiterbar mit Relais oder Opto-Isolation mit der ME-UB Serie.
- ☐ 4 zusätzliche diskrete Digital-I/O-Kanäle auf Schraubklemmen. 32 bit Ereigniszähler.

Das RedLab 1008 ist ein preiswertes, komplettes USB Mini-Mess-Labor im Westentaschen-Format. Für einfache Mess- und Steuer-Vorgänge mit USB ist es die ideale Alternative für das kleine Budget. Also auch eine ideale Lösung zum Beispiel für Ausbildung oder Experiment.

Modell-Übersicht

(Liste der erhältlichen Modelle siehe Web-Shop!)

Modell	Analog-Eingänge	Analog-Ausgänge	Digital-I/O	Zähler
RedLab 1008	8/4 (differenziell), 12 bit	2, 10 bit	24 Port-I/O, 4 diskrete	1, 32 bit
RedPack 1008	RedLab 1008 im Paket mit der Software ProfiLab-Expert ¹⁾			



Technische Daten

Analog-Eingänge	8 single-ended oder 4 differenzielle Kanäle (Schraubklemmen). Bereiche: $\pm 20/\pm 10/\pm 5/\pm 4/\pm 2,5/\pm 2,0/\pm 1,25/\pm 1,0$ V. Rate: Max. 1,2 kS/s, 8 kS/s (bis 4000 Werte). Auflösung: 12 bit differenziell, 11 bit single-ended. Trigger: Quelle programmierbar extern Digital-Kanal 0...3
Analog-Ausgänge	2 Spannungsausgänge (Schraubklemmen). Bereiche 0...5 V. Rate: Software-gesteuert 100 S/s (einzelner Kanal), 50 S/s (2-Kanal). Auflösung: 10 bit
Digital-I/O	Diskret: 4, unabhängig als Ein- oder Ausgänge programmierbar (Schraubklemmen), 5 V/TTL. Eingang, high: 3,0 V min., 15,0 V absolut max.; Eingang, low: 0,8 V max.; Ausgang, keine Last: VS - 0,4 V min., VS typ; Ausgang, 1 mA Last: VS - 1,5 V. Schutz durch 1,5 k Ω Serien-Widerstand Port-I/O: 24 I/O-Kanäle (Sub-D) organisiert in 4x 8 bit Ports, portweise als Ein- oder Ausgänge programmierbar. Alle Pins mit Pull-up nach VS über 47 k Ω . Eingang, high: 2,0 V min., 5,5 V absolut max.; Eingang low: 0,8 V max., -0,5 V absolut min.; Ausgang high: ($I_{OH} = -2,5$ mA) 3,0 V min.
Zähler	1 (Anschluss: Schraubklemme), 32 bit Ereigniszähler: Eingangsfrequenz max. 1 MHz. Pulsbreite: High/low 500 ns min. Eingang low: 0 V min., 1,0 V max.; high: 4,0 V min., 15,0 V max.
Größe	157 x 102 x 40 (LxBxH), mm
Versorgung	Vom PC über USB
Interface	USB 1.1 low-speed (USB 2.0 kompatibel); max. 3 m USB-Kabel
Verbinder	Schraubklemmen, 37-pol. Sub-D Stecker: USB: Typ B
Software	TracerDAQ (Strip-Chart-Recorder, Datenlogger). Universal Library (Hochsprachen-Unterstützung unter Windows 2000, XP, Vista). InstaCAL-Utility (Installation, Kalibrierung, Test). Treiber für LabVIEW. Optional/ Zubehör: TracerDAQ Pro, ProfiLab-Expert ¹⁾
Lieferumfang	RedLab 1008, USB-Kabel, Schraubendreher, Software und Gebrauchsanleitung auf CD. RedPack 1008: ProfiLab-Expert ¹⁾

¹⁾ Beim Paket RedPack 1008 ist ProfiLab-Expert im Lieferumfang. Unter ProfiLab-Expert wird z. T. nicht die volle Abtastrate unterstützt.



Ausführliche Infos und Zubehör im Detail:
www.meilhaus.com/go/redlab



MotionScope M3



Redlake's MotionScope® M3 high-speed CMOS camera combines ease-of-use and value for your high-speed motion application. The MotionScope® M3 offers maximum resolution of 1280 x 1024 at 500 fps with frame rates up to 32,000 fps at reduced resolutions.

Specifically optimized for industrial applications, the innovative Redlake MotionScope® M3 high-speed digital camera architecture puts it in a class by itself. Small, lightweight, stand-alone battery operation, and Firewire network connectivity are just a few attributes of the MotionScope® M3 camera.

The MotionScope® M3 features built-in image memory for storing the recorded high-speed sequence for playback, editing, or downloading to the PC's hard disk. Just choose which image memory option best fits your application requirements. Flexible triggering lets you create the best pre- and post- event trigger settings enabling you to capture perfect images every time.

The MotionScope® M3's internal battery comes standard and provides up to 30 minutes of standalone operation and up to 4 hours in stand-by mode. Since the MotionScope® M3 is self-contained (no bulky processor or tethered cables to contend with) the only connection required is a trigger signal.

Thanks to its intuitive and reliable Windows control software, the MotionScope® M3 is exceptionally simple to set up and operate. Advanced features are included in the standard Image Studio software. The camera is interfaced to your PC via a standard Firewire (IEEE-1394) interface.

Applications: Diagnostics of high speed machinery, Process control, High speed packaging machinery, Laboratory research

Features	Benefits
Up to 1280 x 1024 resolution	High resolution to capture events even at high frame rates
Fast frame rates to 500 fps at full resolution and up to 32,000 fps at reduced resolutions	Capture dynamics of fast processes or events
Supports up to 4 seconds resolution	Extended record time for long events such as animal locomotion
Global Shutter to 4 µseconds	Freeze motion photography of fast moving objects with minimal or no motion blur
Compact packaging	For constrained space applications
Internal battery	For standalone operation

Sample Frame Rates

1.3 GB Memory			
Resolution	Frame Rate	Number of Frames	Duration
1280 x 1024	500 fps	1024	2 seconds
640 x 512	1000 fps	4096	4 seconds
320 x 256	2000 fps	16,384	8 seconds
320 x 128	4000 fps	32,768	8 seconds
160 x 64	8000 fps	65,536	16 seconds
160 x 32	16,000 fps	262,144	16 seconds
160 x 16	32,000 fps	524,288	16 seconds
2.6 GB Memory			
Resolution	Frame Rate	Number of Frames	Duration
1280 x 1024	500 fps	2048	4 seconds
640 x 512	1000 fps	8192	8 seconds
320 x 256	2000 fps	32,768	16 seconds
320 x 128	4000 fps	65,536	16 seconds
160 x 64	8000 fps	262,144	32 seconds
160 x 32	16,000 fps	524,288	32 seconds
160 x 16	32,000 fps	1,048,576	32 seconds

Note: proportions are approximate

MotionScope M3 Performance Specifications

CMOS Imager

Sensor Array	Area array with 12 μm x 12 μm pixels, Color or Monochrome
Image Resolution	1280 x 1024 at 500 fps
Dynamic Range	59 dB at sensor

Memory and Record Rates

On-board Storage	1.3 GB and 2.6 GB models available
Recording Rates	Selectable, up to 32,000 fps
Playback Rates	7.5, 15 fps (full resolution) depending on PC

Camera Control

Shutter	Global Electronic Shutter variable down to 4 μs
Trigger Frame	Variable position from start to the maximum available frame capacity
Trigger Mode	TTL, 5V-tolerant switch closure

Software

Control Software	Imaging Studio; Windows 2000/XP compatible
File Formats	Raw, BMP, TIFF, JPEG, AVI, GIF, JPEG, and MPEG

Mechanical Description

Camera Dimensions	2.6 in (67 mm) H x 2.6 in (67 mm) W x 4.9 in (125 mm) L
Camera Weight	1.87 lb (6.5 Kg)
Camera to PC Interface	IEEE-1394a (Firewire)
Camera Cable Lengths	5m (firewire); optional fiber media convertor for longer distances
Battery capacity	30 min. recording and 4 hr. standby
Lens Compatibility	1" C-mount
Lens Mount	C-mount, F-mount adapter, other adapters available
Hi-G Hub Size	Dimensions and Weight: 7.87"(H) x 4.33"(W) x 2.48" (L) (200 x 110 x 63mm); Weight: <1.0 lb (<0.5Kg)
Hi-G Hub Interface	Camera/Hub Sync Unit/Control PC Network; Trigger In; Power; Sync In, Sync Out

Synchronization

Multiple Cameras / Network	Synchronized using the Sync In and Sync Out connections. When using a high-G hub, cameras may be synchronized to an external source, or to a master camera
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Environmental

Camera Power	+8 to 16 VDC @ 12W
HUB Power	+9 to 36 VDC @ 60W
Shock Hub	100G @ 6ms min. any axis, 1000 cycles
Operating Temperature	-18°C to +45°C Ambient (0°F to 122°F)
Emissions/Safety	CE approved, FCC Class B compliant, UL listed

Input/Output

I/O – Trigger I/O	
Strobe Output (3.3V)	
Power (12V DC)	
IEEE-1394a - Firewire	

Note: Specifications are subject to change.

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Eidesstattliche Erklärung

Ich versichere, dass ich die Arbeit ohne fremde Hilfe und ohne Benutzung anderer als der angegebenen Quellen angefertigt habe und dass die Arbeit in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen hat und von dieser als Teil einer Prüfungsleistung angenommen wurde. Alle Ausführungen, die wörtlich oder sinngemäß übernommen wurden, sind als solche gekennzeichnet.

Fabian Zimmer

Erlangen, 10. März 2013