COLOR-CODED TOMOGRAPHY

B. Ruck
Institute for Hydromechanics
University of Karlsruhe, Germany

Keywords:, *multi-color laser, tomography, flow measurement*

1 INTRODUCTION

The development of fully 3D-measuring techniques in experimental fluid mechanics could not keep up with the development of numerical fluid mechanics. The latter led to the fact that we are able to compute three-dimensional unsteady flows, but often, we cannot validate or verify the results of these computations any longer. Measuring procedures are lacking, which are able to measure whole flow fields or flow volumes temporally with a high resolution. Additionally, it is going to be difficult to deliver experimentally start and boundary conditions for three-dimensional computations.

Existing measuring techniques are limited. To measure qualitatively instantaneous 2-D flow fields, laser light sheet techniques have been developped [1-3]. For quantitative analyses of whole fields, measuring systems like PIV- [4-7] or PTA-systems [8-10] can provide sequences of flow data in subsequent frames. To account for the third velocity component in the plane under consideration, extensions of this techniques have been proposed [11-13]. To analyse whole flow volumes, systems based on stereoscopy or multi-camera detection [14-17] and tomography have been introduced. Those techniques allow to 'freeze' the flow volume instantaneously. The most advanced laser tomography illuminates consecutive light sheets in the flow volume, which are detected each, processed and link by a computer to deliver a 3-D information [18-20].

2 LIMITS OF EXISTING WHOLE VOLUME MEASURING TECHNIQUES

Laser tomography delivers usually sequences of tomograms for only one 'frozen' volume detection. The number of tomograms will be typically between 20 and 100. The volume detection rate (number of 'frozen' volume detections per second) is usually very low and does not suffice to track realistic turbulent flows as might be inferred from the following example. Supposed, we use an image detector of 1k x 1k pixels. Then, the amount of data will be between 20-100 Megabytes for one 'frozen' volume detection. Realistic turbulent flows can easily show characteristical turbulent frequencies of about 100 Hz. To track such flows with a sufficient time resolution, we need to have a volume detection rate of the same order of magnitude. Thus, we end up with 2-10 gigabytes/second of graphical data, which have to be caputered and processed - a quantity of data which can hardly be mastered!

Independently of whether it concerns qualitatively or quantitatively whole volume measuring procedures on the basis of laser tomography, stereoscopy or holography, it is a matter of fact that the ability of these techniques is very poor with respect to a high time resolution. This means that only low volume detection rates can be realized, which are far below those given by turbulent time/frequency scales. It is, especially, the tremendous amount of data needed, which has limited the development of fast 3-D whole volume measuring systems in the past.

3 NEW CONCEPTS

The aim of this contribution is to point out new manageable concepts in laser tomography, which can overcome limiting factors such as insufficient time resolution and an enormous amount of data in order to enable 3-D volume analyses of flow fields with a maximum of temporal resolution. The developments are based on illuminating the flow volume with colored light and on the detection and analysis of scattered light from differently colored areas/layers. The flow volume under consideration can either be illuminated simultaneously by colored light with a color spectrum according the continuous natural spectrum of the white light, or discretely, i.e. by laser light of defined color in spatially and temporally staggered consecutive layers/sheets of the volume. Using these concepts, it might suffice to apply only one camera to extract a full three-dimensional flow information. Two components of this information will be derived from the detected plane, the third will be derived from the color.

3.1 Continuous mode

The simplest possibility of illuminating a flow volume with colored light exists in the application of white light, which is fanned out by a dispersion prism into a continuous spectrum. This color fan can be positioned into the flow volume using a suitable mirror/lens combination. Thus, the whole volume will be coded delivering only one unambiguous color for a specific position along the axis perpendicular to the color fan. If one detects the volume in this direction with a color-sensitive camera, then, colored flow outlines or colored particle traces will be detectable. The spatial position of a colored part of an outline or trace can be identified by the color itself.

Fig. 1 shows the illumination of a flow volume in continuous mode. The continuous mode version seems to represent a passable way at first sight, in order to obtain a fast three-dimensional flow information. However, problems are associated with the analysis of such a colored image. Due to the use of a natural white light spectrum, the separation of colors of adjacent spatial positions will be problematical. The differences in color may be so small that a sufficient resolution, i.e. a precise allocation of space, might be impossible. Additionally, the use of white light has the disadvantage that light is diverging much more rapidly when compared to laser light. It would be better in any case to generate almost parallel con-

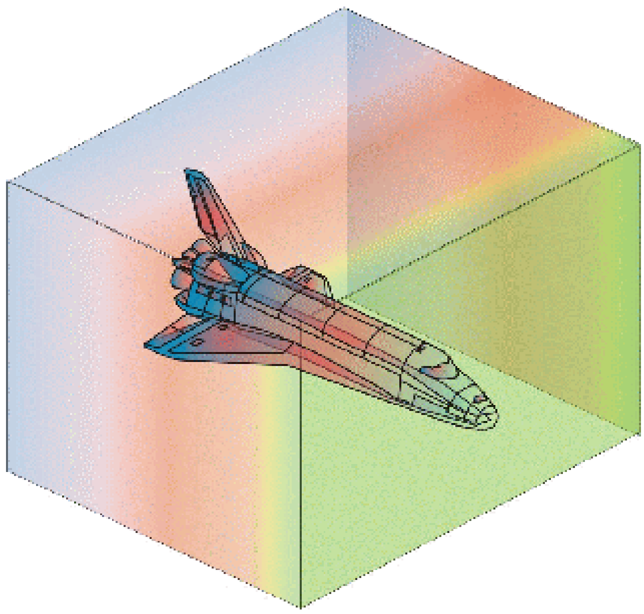


Fig. 1: Simultaneous illumination of a flow volume with colored light according to the natural light spectrum

secutively staggered light sheets of different contrasting colors.

3.2 Discontinuous mode

Following the above mentioned arguments, an optimum color illumination can be realized by using laser light, however, the problem is to find a laser, which generates light of any wavelength. The problem can be solved by using a so-called white light laser, which produces simultaneously a red, green and blue line, and whose multi-line beam is converted by an acousto-optical cell. i.e. by mixing of the color components, into the desired color. Since this procedure can only be achieved in a temporally consecutive way, a tomographical arrangement must be designed, which ensures the spatially staggered positioning of the colored light sheets in the volume. In this way, a **S**canning **M**ulti-color **L**aser **T**omography system (SMLT) can be realized [21-23], see Fig. 2.

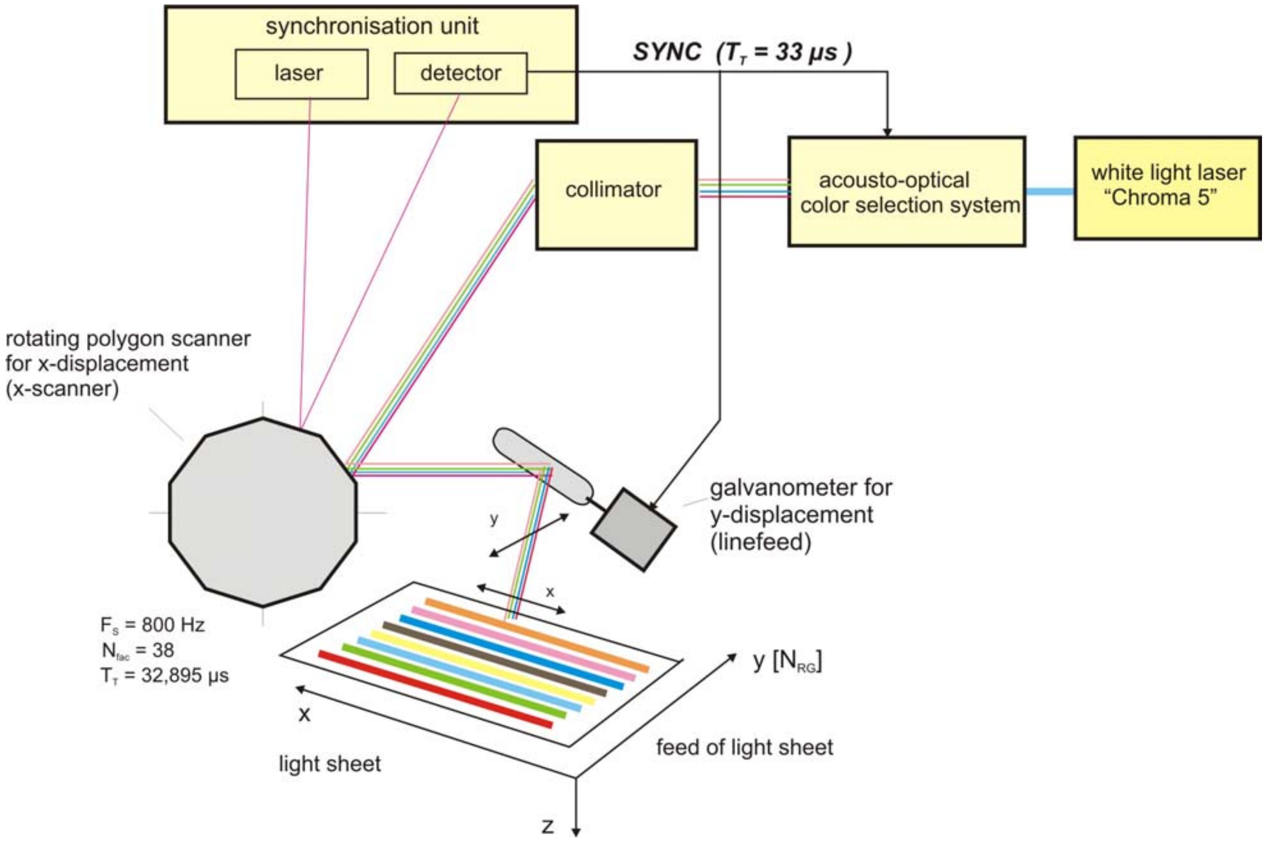


Fig. 2: Generation of differently colored laser light sheets

To lay out such a tomography system, first of all, the number of different colors for spatial separation within the volume under consideration must be determined. In order to obtain colored light sheets variable in thickness, more than one line of the same color can be combined yielding a 'thick' color light sheet, see Fig. 3. The decisive system constant for computation is the time needed for one line (33 µsec), which is given by the angular frequency of the polygon and the number of facets. Setting the parameters'number of colors', 'time for a complete volume scan', 'number of lines per color' and 'volume length' allow to realize a variety of colored light sheet configurations including well defined spacings in the volume, if needed.

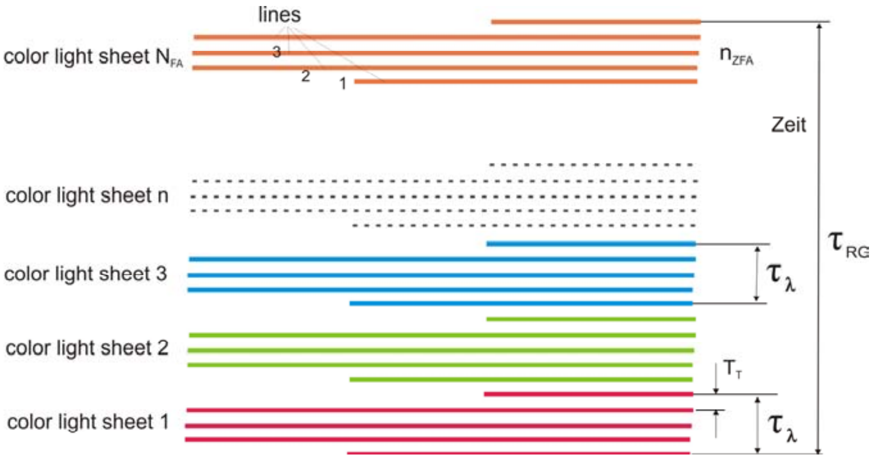


Fig. 3: Generating 'thick' colored light sheets by several lines of the same color

The procedure of the new color-coded tomography differs from that of single-color tomography in the way that despite of tomographical illumination no tomograms will be detected. Instead, an 'integral' image of the volume is detected and processed. Thus, for tracking turbulent flows in a volume, not the number of tomograms per 'frozen' volume detection times the number of volume detections is the crucial number for the lay-out of the system, but only the number of 'integral' images. In this way, the number of detected images is about 2 magnitudes lower than the number in single-color tomography, which makes temporally high-resolved SMLT managable with existing high speed camera systems and reduces the amount of data enormously. Fig 4 sketches the application of the new principle for bluff body investigations. As can be seen, contours can be extracted from the volume easily with only one integral image.

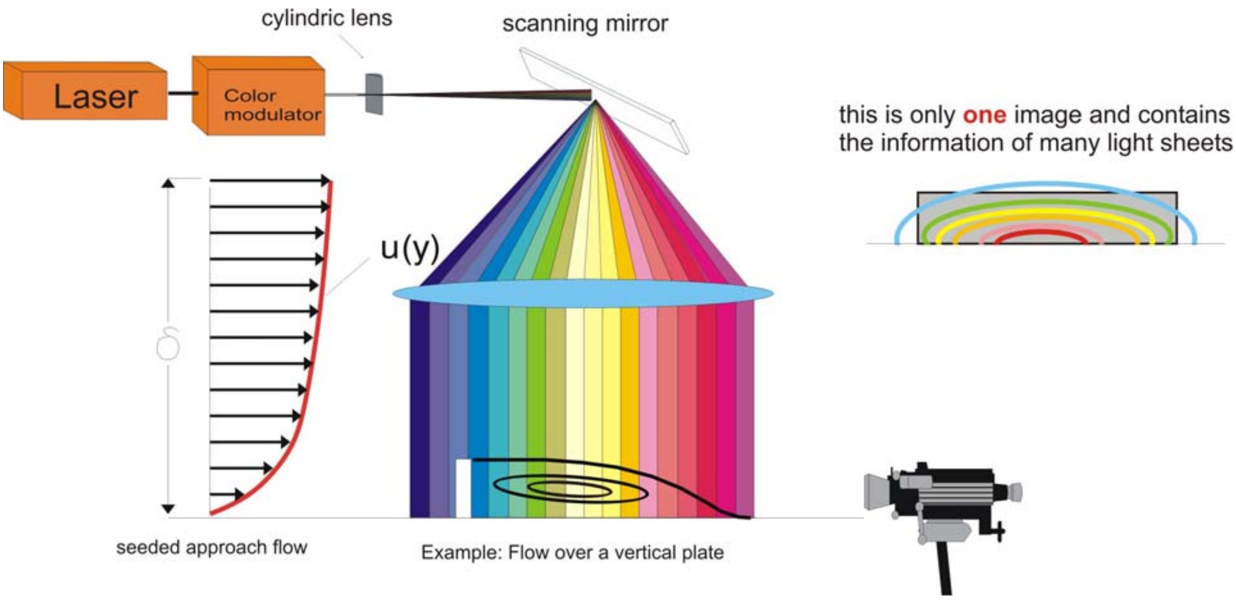


Fig. 4: Application of color-coded tomography for bluff body investigations

4 COLOR-CODED PTV AND PIV TECHNIQUE

The new multi-colour principle (SMLT) can be used for the extension of existing whole field measuring techniques (PTV, PIV). In Fig. 5 the application of the new principle is shown for PTV. In PTV, a particle trajectory will be represented as a colored line. The amount of the velocity can be inferred from the image plane (x, y-coordinates) and from the start - and final color of the trajectory (z-coordinate). The direction of the particle trajectory can be obtained easily by applying additional coding procedures, e.g. [22]. With PIV, the direction can be deduced from the

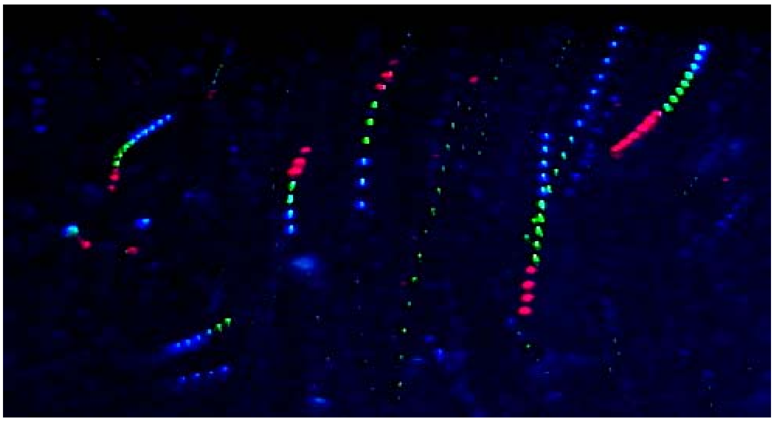
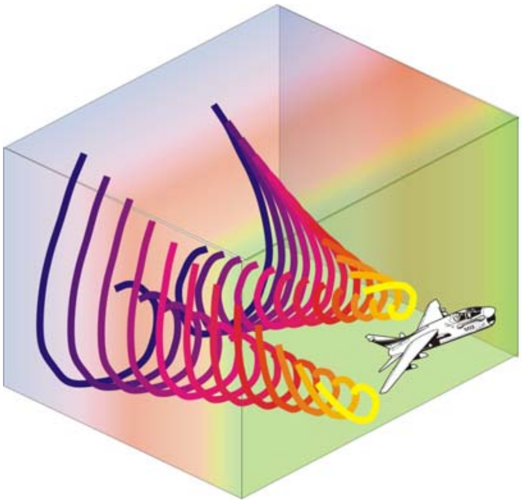


Fig. 5: Particle trajectories in a flow field visualized with color-coded tomography

sequence of double exposed frames. PIV analyses the displacements of illuminated particles in the flow. With the SMLT principle, a DPIV-system can be realized delivering pairs of differently colored points. Based on the evaluation of these colored pairs, the standard PIV processing yields the plane displacements (x,y) and the color delivers the displacements in the third direction (z). Thus, with relatively small changes of the experimental set-up (color-sensitive camera, software), a standard 2-D-DPIV-system can be converted into a 3-D-DPIV-system.

5 FURTHER RESEARCH

Using only one 'integral' image of a single camera will certainly reduce the spatial resolution within the volume under consideration when compared to a standard tomographical, multi-frame-based technique. However, this does not raise severe difficulties, since the development of image sensors in puncto number of pixels is proceeding fast. Another problem associated with the overlapping of flow outlines or traces in only one detection direction may occur. In such cases, outline or trajectory defects will be detected, see Fig. 6. However, the application of image processing techniques can help to repair such defects. Nevertheless, there is a need of further research in this field. A further difficulty, which is associated with all existing image recording technique is the depth of focus. It is planned to develop a piezo-based lens feed to readjust the focal length and to account for the displacement of the different colored laser light sheets in the volume during image exposure.



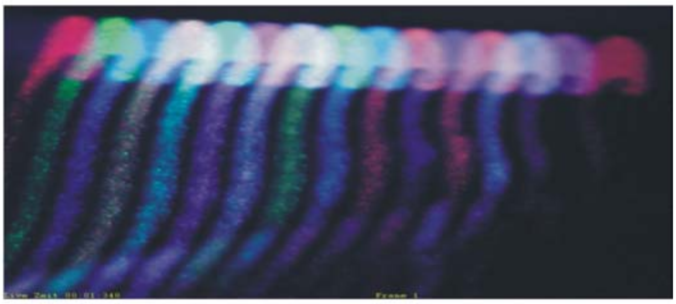


Fig. 6: Flow outlines or particle trajectories can intersect in the direction of detection. The detected outlines or trajectories may show defects, which can be repaired by image processing techniques.

ACKNOWLEDGEMENTS

The author would like to express his thanks to the Deutsche Forschungsgemeinschaft DFG/Bonn for the funding of this research within the project No. Ru 345/27-1. Thanks are also due to Dr. B. Pavlovski for his experimental support.

REFERENCES

[1] Beiser, L., 1970: Laser Scanning Systems; in: "Laser Application", Academic Press, New York

[2] Schmitt, F.; Ruck, B., 1986: "Laserlichtschnittverfahren zur qualitativen Strömungsanalyse", Laser und Optoelektronik, Nr. 2 (1986), pp. 107-118.

[3] Ruck, B., 1990: "Laserlichtschnittverfahren und digitale Videobildverarbeitung", in Lasermethoden in der Strömungsmeß-technik, Ruck, B. (ed.), AT-Fachverlag Stuttgart, 10, 367-402, ISBN: 3-921 681-01-4

[4] Merzkirch, W., 1990: "Laser-Speckle-Velocimetrie", in: Lasermethoden in der Strömungsmechanik, (Hrsg. Ruck, B.), AT-Fachverlag, Stuttgart, S. 71-97.

[5] Adrian, R., 1991: "Particle-Imaging Techniques for Experimental Fluid Mechanics". Annual Review of Fluid Mechanics, V. 23, pp. 261-304.

[6] Buchhave, P., 1992: "Particle Image Velocimetry - Status and Trends", Experimental Thermal and Fluid Science 5, pp. 586-604

[7] Raffel, M., Kompenhans, J., 1995: "Anwendung der PIV in stark dreidimensionalen Strömungen", Proc. der 4. Fachtagung Lasermethoden in der Strömungsmeßtechnik, Rostock, Shaker Verlag , pp. 38.1-38.3.

[8] Agüi, J.C.; Jimenez, J.,1987: "On the Performance of Particle Tracking", J.Fluid Mech. 185, S. 447-468

[9] Adamczyk, A.A.; Rimai, L., 1988: "2-Dimensional Particle Tracking Velocimetry (PTV): Technique and Image Processing Algorithms", Experiments in Fluids 6, S. 373-380

[10] Dracos, Th., 1996: "Particle Tracking Velocimetry (PTV) Basic Concepts". In: Dracos, Th.: Three-Dimensional Velocity and Vorticity Measuring and Image Analysis Techniques. Bd. III. Kluwer Academic Publishers, ISBN 0-7923-4256-9, S. 155-160

[11] Kimura, I., Kohno, Y., 1991: "Measurements of three-dimensional velocity vectors in a flow field based on spatio-temporal image correlation", Proceedings of the 3. Int. Symp. FLUCOME, pp. 609-615

[12] Brücker, C., 1996: "3-D-PIV via spatial correlation in a color-coded light sheet", Experiments in Fluids, 21, pp. 312-314

[13] Cenedese, A., Paglialunga, A., 1998: "A new technique for the determination of the third velocity component with PIV, Experiments in Fluids, 8, pp. 228-230

[14] Kasagi, N.; Nishino, K., 1990: "Probing Turbulence with Three-Dimensional Particle Tracking Velocimetry". In: Rodi, W. und Ganic, E.N.: Engineering Turbulence Modelling and Experiments. Elsevier Sci. Publ. Co., ISBN 0-444-01563-9, pp. 299-314

[15] Prasad, R., Adrian, R., 1993: "Stereoscopic particle image velocimetry applied to liquid flows", Exp. Fluids, 15, pp. 49-60.

[16] Hinrichs, H., Hinsch, K., D., 1995: "Hochauflösende Stereofotografie in der PIV", Proc. der 4. Fachtagung Lasermethoden in der Strömungsmeßtechnik, Rostock, Shaker Verlag Aachen, S. 35.1-35.3.

[17] Cenedese, A.; Moroni, M.; Viotti, P., 1997: "Velocity Field in a Porous Medium by Means of Stereoscopic Particle Tracking Velocimetry". Proc. of the 7th Int. Conf. on Laser Anemometry, University of Karlsruhe, ISBN 3-9805613-0-5, S. 467-474

[18] Prenel, J.P., Porcar, R., El Rhassouli, A., 1989: Three dimensional flow analysis by means of sequential and volumic laser sheet illumination. Experiments in Fluids 7, Springer Verlag, pp. 133-137.

[19] Yoda, M., Hesselink, L., 1990: A three dimensional visualisation technique applied to flow around a delta wing. Experi-ments in Fluids 10, Springer Verlag, pp. 102-108.

[20] Ruck, B., Pavlovski, B., 1998: "Entwicklung eines Laserlichtschnitt-Tomographiesystems zur Erfassung von Strömungs-strukturen", Laser & Optoelektronik, 30 (4), S. 61-70

[21] Arndt, S., Heinen, Ch., Reymann, K., Ruck, B., 2000: "Einsatz eines neuartigen Mehrfarben-Laserlichtschnitt-Tomographieverfahrens zur Analyse räumlicher Strömungsfelder", Proceedings der 8. Fachtagung "Lasermethoden in der Strö-mungsmeßtechnik", Universität München, paper 55

[22] Ruck, B., 1994: "Ein neues laseroptisches Verfahren zur Sichtbarmachung und Echtzeit-Vektorisierung von Strömungsfel-dern", Laser und Optoelektronik, 26, Heft 5, 67-71

[23] Heinen, C., 2001: „Weiterentwicklung und Verifizierung der Einsatztauglichkeit neuartiger laseroptischer Tomographiever-fahren in der Strömungsmesstechnik", Dissertation an der Universität Karlsruhe, erschienen: Dissertationsreihe der Fa. Robert BOSCH GmbH